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RESEARCH ARTICLE

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Hydrogen production from water splitting on CdS-based photocatalysts using solar light

Abstract Hydrogen energy has been regarded as the most promising energy resource in the near future due to that it is a clean and sustainable energy. And the heterogeneous photocatalytic hydrogen production is increasingly becoming a research hotspot around the world today. As visible light response photocatalysts for hydrogen production, cadmium sulfide (CdS) is the most representative material, the research of which is of continuing popularity. In the past several years, there has been significant progress in water splitting on CdS-based photocatalysts using solar light, especially in the development of co-catalysts. In this paper, recent researches into photocatalytic water splitting on CdS-based photocatalysts are reviewed, including controllable synthesis of CdS, modifications with different kinds of cocatalysts, solid solution, intercalated with layered nanocomposites and metal oxides, and hybrids with graphenes etc. Finally, the problems and future challenges in photocatalytic water splitting on CdS-based photocatalysts are described.

Keywords hydrogen, photocatalysis, solar conversion, cadmium sulfide (CdS) complex

1 Introduction

As fossil fuels are likely to be exhausted in the near future and bring lots of serious environmental problems, hydrogen, a new renewable and no-polluting energy, has been considered as a promising candidate to solve these problems. There are different ways to get hydrogen from water such as electrolysis of water, but most of them are costly. In various interesting reactions, the hydrogen production from photocatalytic water splitting by sunlight is potentially one of the most promising ways for the photochemical conversion and storage of solar energy. Since the evolution of hydrogen and oxygen on TiO_2 and Pt counter electrodes under the irradiation of ultraviolet (UV) light was reported by Fujishima and Honda in 1972 [1], photocatalysis has been receiving much attention and studies have been extensively conducted on converting solar energy into clean hydrogen energy. The mechanism of photocatalytic of water is illustrated in Fig. 1, in which TiO_2 was taken as an example [2]. The band gap (between valance band and conductance band) of TiO_2 is approximately 3.0 eV. Electronic transition from valance band to conductance band can be activated by light radiation whose energy should be greater than or equal to its band gap. Consequently, the electron and hole pairs are formed in conductance band and valance band, which can decompose water into hydrogen and oxygen respectively. Up to the present, various kinds of efficient hydrogen-evolution photocatalysts have been reported which can mainly be divided into the titanium dioxide system [3–7] which also contains hybrids of TiO_2 [8,9]; metal sulfides, nitrides and phosphides [10–13]; the tantalate and niobate system [14–18]; and composite catalysts [19–23]. However, most of these photocatalysts are only active under UV light, which accounts for only approximately 3%–5% of the solar spectrum on the surface of the earth.

Cadmium sulfide (CdS) has a band-gap energy (E_g) of 2.4 eV that suits very well with the solar spectrum as shown in Fig. 2, which has received much attention and has been studied widely. However, CdS is not stable in aqueous solutions under irradiation due to photocorrosion. Furthermore, the photocatalytic activity of individual CdS is not so efficient. In order to solve these problems, many researchers mainly focus their attention on material preparation, where different morphology and crystal CdS are synthetized; material modifications; and the system of photocatalytic water splitting to improve the photoactivity.

In this paper, the current research focuses on the improvement of CdS photocatalytic activity are reviewed

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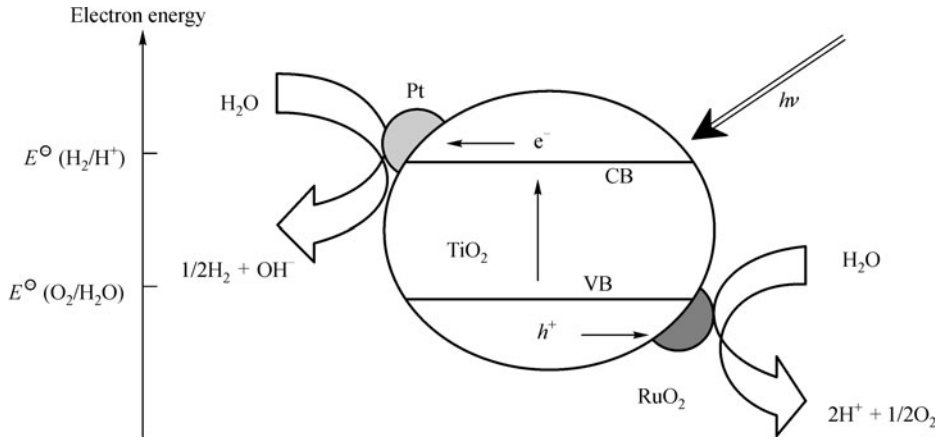

Fig. 1 Mechanism of the photocatalytic of water into H_2 and O_2 on TiO_2 [2]

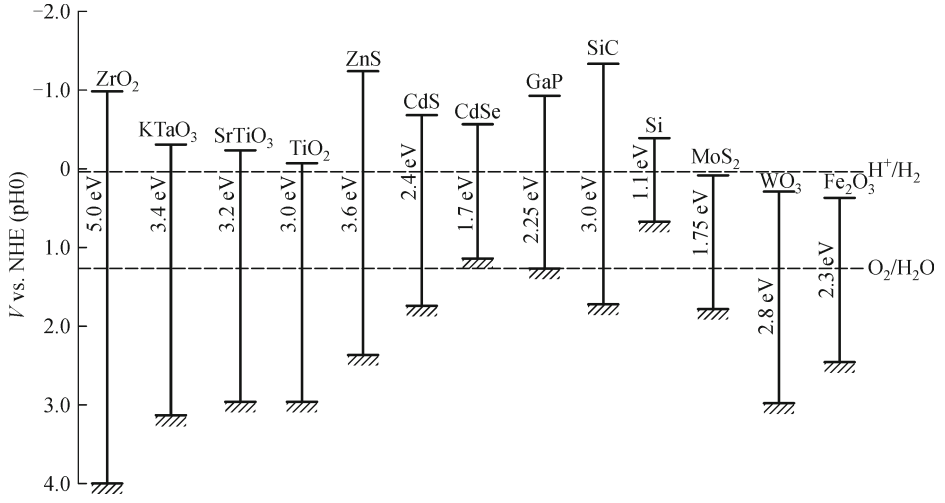

Fig. 2 Relationship between band structure of semiconductor and redox potentials of water splitting [24]

and discussed. In addition, future trends of research on photocatalytic water splitting with CdS are presented.

2 Controllable synthesis of CdS for photocatalytic hydrogen evolution

The photocatalytic properties of CdS semiconductor materials depend not only on the particle size but also the morphology [25–27]. So different synthesis methods are attempted to prepare CdS with different nanostructured and high BET surface area for improving its photoactivity [28–32]. Liu et al. [28] have prepared CdS hollow nanoparticle chains through a facile and efficient ultrasonic-template method. Other shapes of CdS nanostructures, such as nanorods, hollow nanorods, multipods, quasi-nanospheres, hollow nanospheres, nanoshuttles, nanowires, nanotubes, nanosheets have also been reported [29–32]. Li et al. [31] have obtained solid nanospheres (s-CdS), hollow nanospheres (h-CdS) and nanorods (r-CdS) by controlling only the hydrothermal temperatures. They have also revealed the performance of different hydrogen evolutions as presented in Fig. 3. Bao et al. [32] synthesized porous nanosheets and hollow nanorods CdS by a two-step aqueous route. The quantum yield could come to 60.34% at 420 nm after loaded with Pt.

Quantum dots are also used to improve the photocatalytic acivity of catalysts because of its special properties. Yu et al. [33] prepared CdS quantum dots-sensitized $Zn_{1-x}Cd_xS$ solid solutions by a simple cation exchange. It showed high visible-light photocatalytic H_2-production activity even without a Pt co-catalyst.

3 Modifications of CdS

3.1 Loaded with cocatalysts

Besides preparing CdS with different morphology and particle size, co-catalysts also play an important role in

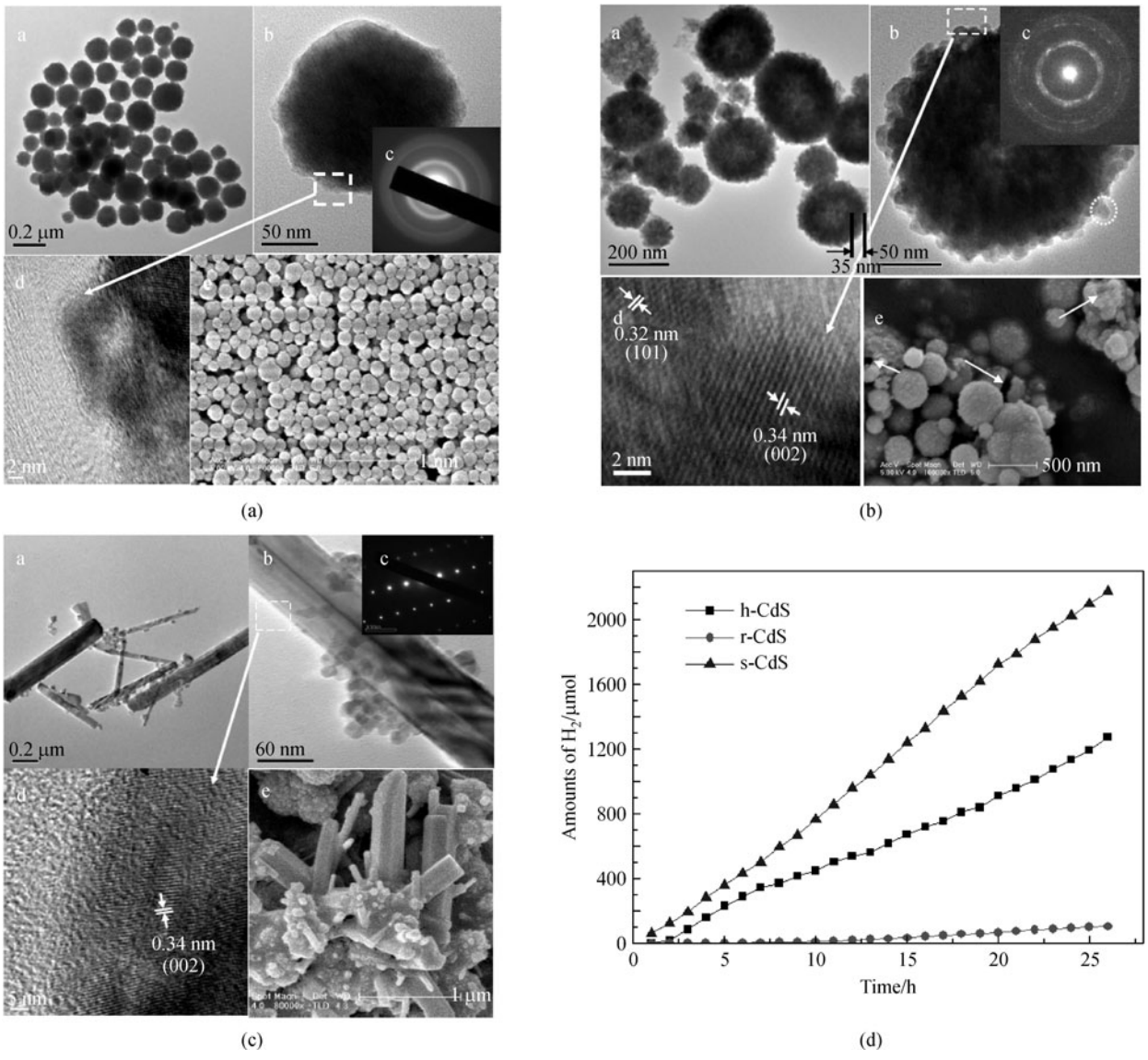

Fig. 3 Electron microscopic photos [30]
(a) Solid nanospheres (s-CdS); (b) hollow nanospheres (h-CdS); (c) nanorods (r-CdS); (d) hydrogen evolution activity

stimulating charge transfer and reducing the recombination of photo-induced charges, thereby enhancing the photocatalytic activity of CdS. The efficient photocatalytic co-catalysts usually contain noble metals (Pt, Au, Rh, RuO_2, etc.) [34–39]. Luo et al. [39] have prepared CdS loaded with dual co-catalysts including PdS and Pt as the oxidation and reduction co-catalysts, respectively. As demonstrated in Fig. 4, electrons and holes can be transferred at the same time. The quantum efficiency of photocatalytic hydrogen production can reach 93% in the presence of sacrificial reagents under visible light.

Although good photocatalytic performance of CdS can be achieved in the presence of noble metals co-catalysts, it is necessary to explore non-noble metals to reduce the cost of renewable H_2 production. The traditional efficient non-noble metals co-catalysts are nickels (Ni, NiO, NiS, NiO_x) [38–40]. However, several researches have focused on the modification of CdS with metal sulfides (MoS_2, WS_2) recently, which supplies a new way to improve the performance of CdS [41,42]. MoS_2 is an excellent H_2 evolution co-catalyst. Furthermore, the junctions formed between MoS_2 and CdS also play an important role in enhancing the photocatalytic activity of CdS. Thus, the 0.2 wt% MoS_2/CdS catalyst demonstrates even higher activity than other noble metal co-catalysts as tabulated in Table 1 [42]. W_2S plays the same role as MoS_2 in enhancing the photocatalytic activity of CdS [41].

3.2 Intercalated with layered nanocomposites and metal oxides

In order to improve the photocatalytic properties, CdS

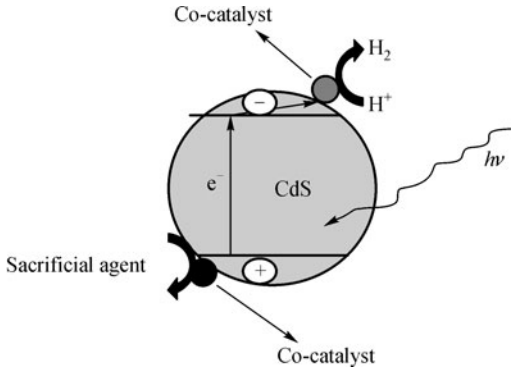

Fig. 4 Mechanism of photocatalytic H_2 -evolution on CdS loaded with co-catalysts

Table 1 Rate of H_2 evolution on CdS loaded with different co-catalysts under visible light ($\lambda > 420$ nm)

Sample	Evolved H_2/(μmol·h^{-1})	Reaction conditions
CdS	15	0.1 g catalyst 10% (vol) lactic solution (200 mL); light source , xenon Lamp (300 W) with a cutoff filter
1 wt% Pt/CdS	355	
1 wt% Ru/CdS	293	
1 wt% Rh/CdS	207	
1 wt% Au /CdS	45.5	
0.1 wt% WS_2/CdS	420	
0.2 wt% MoS CdS	533	

nanoparticles are often incorporated in the interlayer of some particulate metal oxides. As shown in Fig. 5, the incorporation of CdS nanoparticles into the interlayer of layered metal oxides suppresses particle growth while nanoheterojunctions are formed easily between the host layer and the CdS. Thus, photogenerated electrons are quickly transferred through the nanostructure while the recombination between the photo-induced electron and the hole is effectively suppressed. Consequently, the photocatalytic evolution of hydrogen is enhanced [38].

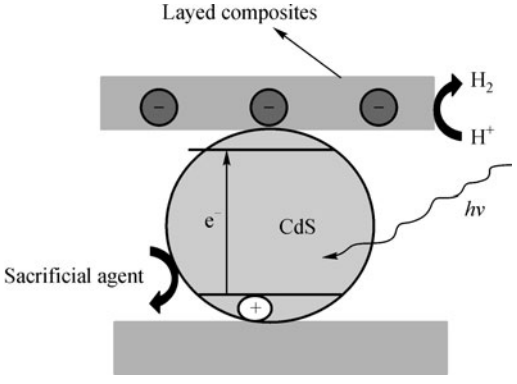

Fig. 5 Mechanism of photocatalytic H_2 evolution on CdS intercalated with layered nanocomposites

As listed in Table 2, the photocatalytic hydrogen evolution of CdS intercalated with layered nanocomposites is superior to simple CdS and the physical mixture of CdS and metal oxides. Further, the activity of CdS intercalated with layered nanocomposites is dependent on hostlayer. The substitution of Nb for partial Ti can bring the quick transfer of the electrons photogenerated in CdS through the host layer into the surface of photocatalysts, Thus, the hydrogen evolution increases [38].

Recently, the Z-scheme has been investigated to split water into hydrogen and oxygen [43,44]. Tada et al. [45] have designed a CdS-Au-TiO_2 three-component nanojunction system imitating natural photosynthesis. This three-component system exhibit a high photocatalytic activity, far exceeding those of the single- and two-component systems, as a result of vectorial electron transfer driven by the two-step excitation of TiO_2 and CdS.

Other CdS intercalated with metal oxides or sulfides and the heterojunction between them have also been extensively studied [46–51]. Barpuzary et al. [51] have prepared high surface area CdS using Al_2O_3 and ZnO as templates by a hydrothermal route. The apparent quantum yields of hetero-system-based CdS@Al_2O_3 and CdS@ZnO can account to 11% and 15% respectively. One-dimensional heterostructures of CdS nanowires decorated with hematite nanoparticles and magnetite microsphere have been synthesized via a two-step solvothermal deposition method [52]. The enhanced photocatalytic activity under visible light happens on account of the help of heterostructures, which can facilitate charge separation. Li et al. [53] have fabricated CdS/TiO_2NTs in which CdS is incorporated into the TiO_2 nanotubes homogeneously. Because of the quantum size effect and the potential gradient at the interface between CdS nanoparticles and TiO_2 nanotubes, the CdS/TiO_2NTs showed higher activity for hydrogen production under visible light.

3.3 Solid solution

The solid solution is often used as an efficient way to improve the activity and stability of CdS [54–57]. With the help of insert metals, the electron-hole recombination and photocorrosion can be prevented efficiently. Therefore, the photocatalytic activity and stability of catalysts can be enhanced apparently [55]. For instance, Ikeue et al. [56] have synthesized the composite sulfide system ($Mn_{1-x}Cd_xS$) by a hydrothermal method and found that the high photocatalytic activity of the $Mn_{1-x}Cd_xS$ system is caused by low-crystalline. Moreover, $Mn_{1-x}Cd_xS$ system showed better tolerance to photocorrosion compared to single CdS. On the other hand, the band structure of $Mn_{1-x}Cd_xS$ system could also be controlled through controlling components and their contents of solid solution. As is known, the band gap of CdS and ZnS are 2.20 and 3.12 eV respectively. And the band gap position of the solid solutions can be adjusted by changing the ratio

Table 2 Resultant properties of CdS and CdS-incorporated composites [41]

Sample	Bandgap/eV	CdS content/wt%	Specific surface area/($m^2 \cdot g^{-1}$)	Evolved H_2/($mmol \cdot m^{-2} \cdot h^{-1}$)[a]
CdS[b]	2.4	–	20.5	3.24
$CdS/KTiNbO_5$	2.6	6.5	10.3	3.68
$CdS/K_2Ti_4O_9$	2.6	10.2	12.4	3.80
$CdS/K_2Ti_{3.9}Nb_{0.1}O_9$	2.5	19.5	19.3	4.70
CdS/ $K_2Ti_{3.9}Nb_{0.1}O_9$[c]	–	–	–	3.20

Notes: [a]—Rate of H_2 evolution under xenon lamp (300 W) in the aqueous solution of Na_2S (0.1 M, 20 ml); [b]—a neat CdS powder; [c]—physical mixture of 20 wt% CdS + 80 wt% $K_2Ti_{3.9}Nb_{0.1}O_9$

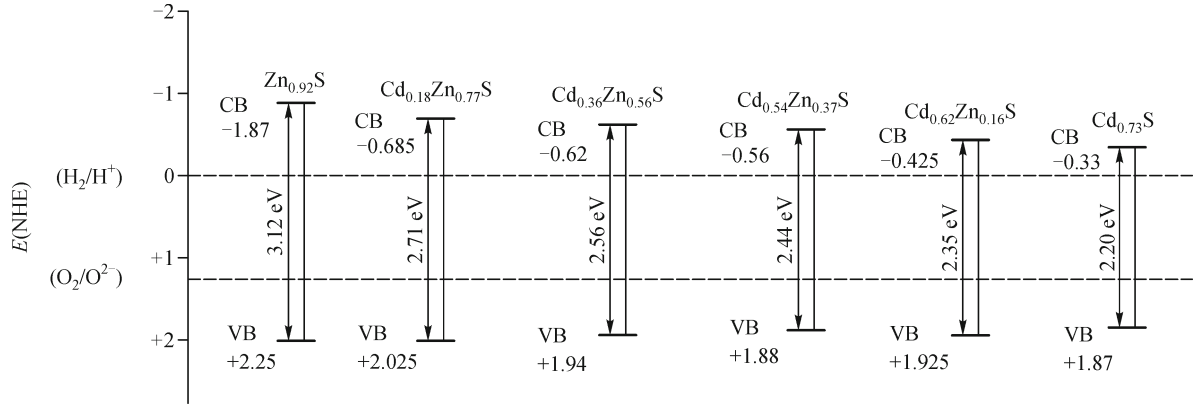

Fig. 6 Conduction and valence band potentials of $Zn_xCd_{1-x}S$ [50]

of the composition of CdS to that of ZnS as displayed in Fig. 6 [54], which is important for high efficient and stable photocatalysts design and preparation.

3.4 Hybrids with graphenes

Because of the special conductivity and conjugated system derived from the unique sp^2 hybrid carbon skeleton structure, graphene has been regarded as an ideal conductive support for nanoparticles to form hybrid materials with CdS for the purpose of photocatalytic activity improvement [58–62]. As exhibited in Fig. 7, CdS or its solid solutions can be excited by solar to generate electrons and holes. Besides the function of heterostructures and high surface area of catalyst hybrids, the photogenerated electrons are transferred to graphene while holes are left in CdS since the conduction band of CdS is more negative [59]. Thus, the recombination of electron-hole pairs is suppressed and the lifetime of charge carriers is prolonged. Consequently, the photoactivity can be improved efficiently and the apparent quantum efficiency can be up to 23.4% at 420 nm [58].

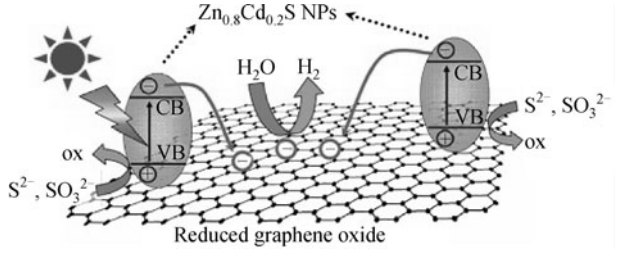

Fig. 7 Mechanism of photocatalytic hydrogen production on reduced graphene oxide-$Zn_xCd_{1-x}S$ [54]

4 Conclusions

In this paper, current researches of hydrogen production with CdS-based photocatalysts are reviewed and discussed. Great progress has been made in the research of high efficient photocatalytic hydrogen production with CdS. Through loading cocatalysts, intercalating with layered nanocomposites, hybrids with graphenes or solid solution can favor electron transfer and suppress the recombination of electron-hole pairs. Thus the photocatalytic activity and stability can be improved apparently. These may provide reference for the preparation of more efficient CdS-based photocatalysts for the purpose of hydrogen production. However, few studies on suppressing photocorrosion have been conducted to improve the stability of CdS. Consequently, new and advanced ways have to be further investigated on CdS to enhance its photocatalytic water splitting performance.

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References

1. Fujishima A, Honda K. Electrochemical photolysis of water at a semiconductor electrode. Nature, 1972, 238(5358): 37–38
2. Shangguan W F. Progress in hydrogen production from water splitting using solar light. Chinese Journal of Inorganic Chemistry, 2001, 17(5): 619–624
3. Hosono E, Fujihara S, Imai H, Honma I, Masaki I, Zhou H S. One-step synthesis of nano-micro chestnut TiO_2 with rutile nanopins on the microanatase octahedron. ACS Nano, 2007, 1(4): 273–278
4. Chuangchote S, Jitputti J, Sagawa T, Yoshikawa S. Photocatalytic activity for hydrogen evolution of electrospun TiO_2 nanofibers. ACS Applied Materials & Interfaces, 2009, 1(5): 1140–1143
5. Weng C C, Hsu K F, Wei K H. Synthesis of arrayed TiO_2 needlelike nanostructures via a polystyrene-block-poly (4-vinylpyridine) diblock copolymer template. Chemistry of Materials, 2004, 16 (21): 4080–4086
6. Wang H Q, Wu Z B, Liu Y. A simple two-step template approach for preparing carbon-doped mesoporous TiO_2. Journal of Physical Chemistry C, 2009, 113(30): 13317–13324
7. Wang D A, Liu Y, Wang C W, Zhou F, Liu W M. Highly flexible coaxial nanohybrids made from porous TiO_2 nanotubes. ACS Nano, 2009, 3(5): 1249–1257
8. Irie H, Watanabe Y, Hashimoto K. Nitrogen-concentration dependence on photocatalytic activity of $TiO_{2-x}N_x$ powders. Journal of Physical Chemistry B, 2003, 107(23): 5483–5486
9. Khan S U, Al-Shahry M, Ingler W B Jr. Efficient photochemical water splitting by a chemically modified *n*-TiO_2. Science, 2002, 297 (5590): 2243–2245
10. Yan H J, Yang J H, Ma G J, Wua G P, Zong X, Lei Z B, Shi J Y, Li C. Visible-light-driven hydrogen production with extremely high quantum efficiency on Pt-PdS/CdS photocatalys. Journal of Catalysis, 2009, 266(2): 165–168
11. Maeda K, Saito N, Lu D, Inoue Y, Domen K. Photocatalytic properties of RuO_2-loaded β-Ge_3N_4 for overall water splitting. Journal of Physical Chemistry C, 2007, 111(12): 4749–4755
12. Hara M, Hitoki G, Takata T, Kondo J N, Kobayashi H, Domen K. TaON and Ta_3N_5 as new visible light driven photocatalysts. Catalysis Today, 2003, 78(1–4): 555–560
13. Ohmori T, Mametsuka H, Suzuki E. Photocatalytic hydrogen evolution on InP suspension with inorganic sacricial reducing agent. International Journal of Hydrogen Energy, 2000, 25(10): 953–955
14. Kato H, Asakura K, Kudo A. Highly efficient water splitting into H_2 and O_2 over lanthanum-doped $NaTaO_3$ photocatalysts with high crystallinity and surface nanostructure. Journal of the American Chemical Society, 2003, 125(10): 3082–3089
15. Yoshioka K, Petrykin V, Kakihana M, Kato H, Kudo A. The relationship between photocatalytic activity and crystal structure in strontium tantalates. Journal of Catalysis, 2005, 232(1): 102–107
16. Domen K, Kudo A, Tanaka A, Onishi T. Overall photodecomposition of water on a layered niobiate catalyst. Catalysis Today, 1990, 8 (1): 77–84
17. Wang D F, Zou Z G, Ye J H. A new spinel-type photocatalyst $BaCr_2O_4$ for H_2 evolution under UV and visible light irradiation. Chemical Physics Letters, 2003, 373(1–2): 191–196
18. Zou Z G, Ye J H, Arakawa H. Role of R in Bi_2RNbO_7 (R = Y, Rare Earth): Effect on band structure and photocatalytic properties. Journal of Physical Chemistry, 2002, 106(3): 517–520
19. Maeda K, Teramura K, Lu D L, Takata T, Saito N, Inoue Y, Domen K. Photocatalyst releasing hydrogen from water. Nature, 2006, 440 (7082): 295
20. Wang X C, Maeda K, Lee Y, Domen K. Enhancement of photocatalytic activity of $(Zn_{1+x}Ge)(N_2O_x)$ for visible-light-driven overall water splitting by calcination under nitrogen. Chemical Physics Letters, 2008, 457(1–3): 134–136
21. Tsuji I, Kato H, Kobayashi H, Kudo A. Photocatalytic H_2 evolution reaction from aqueous solutions over band structure-controlled $(AgIn)_xZn_{2(1-x)}S_2$ solid solution photocatalysts with visible-light response and their surface nanostructures. Journal of the American Chemical Society, 2004, 126(41): 13406–13413
22. Liu H, Yuan J, Shangguan W F, Teraoka Y. Visible-light-responding $BiYWO_6$ solid solution for stoichiometric photocatalytic water splitting. Journal of Physical Chemistry C, 2008, 112(23): 8521–8523
23. Shangguan W F. Hydrogen evolution from water splitting on nanocomposite photocatalysts. Science and Technology of Advanced Materials, 2007, 8(1,2): 76–81
24. Kudo A, Miseki Y. Heterogeneous photocatalyst materials for water splitting. Chemical Society Reviews, 2009, 38(1): 253–278
25. Agarwal R, Barrelet C J, Lieber C M. Lasing in single cadmium sulfide nanowire optical cavities. Nano Letters, 2005, 5(5): 917–920
26. Sathish M, Viswanathan B, Viswanath R P. Alternate synthetic strategy for the preparation of CdS nanoparticles and its exploitation for watersplitting. International Journal of Hydrogen Energy, 2006, 31(7): 891–898
27. Grzelczak M, Correa-Duarte M A, Salgueirino-Maceira V, Giersig M, Diaz R, Liz-Marzán L M. Photoluminescence quenching control in quantum dot-carbon nanotube composite colloids using a silica-shell spacer. Advanced Materials (Deerfield Beach, Fla.), 2006, 18 (4): 415–420
28. Liu J K, Luo C X, Yang X H, Zhang X Y. Ultrasonic-template method synthesis of CdS hollow nanoparticle chains. Materials Letters, 2009, 63(1): 124–126
29. Wang X L, Feng Z C, Fan D Y, Fan F T, Li C. Shape-controlled synthesis of CdS nanostructures via a solvothermal method. Crystal & Growth Design, 2010, 12(12): 5312–5318
30. Yang X H, Wu Q S, Li L, Ding Y P, Zhang G X. Controlled synthesis of the semiconductor CdS quasi-nanospheres, nanoshuttles, nanowires and nanotubes by the reverse micelle systems with different surfactants. Colloid and Surfaces A. Physicochemical and Engineering Aspects, 2005, 264(1–3): 172–178
31. Li C L, Yuan J, Han B Y, Shangguan W F. Synthesis and photochemical performance of morphology-controlled CdS photocatalysts for hydrogen evolution under visible light. International

Journal of Hydrogen Energy, 2011, 36(7): 4271–4279
32. Bao N Z, Shen L M, Takata T, Domen K. Self-templated synthesis of nanoporous CdS nanostructures for highly efficient photocatalytic hydrogen production under visible light. Chemistry of Materials, 2008, 20(1): 110–117
33. Yu J G, Zhang J, Jaronic M. Preparation and enhanced visible-light photocatalytic H_2-production activity of CdS quantum dots-sensitized $Zn_{1-x}Cd_xS$ solid solution. Green Chemistry, 2010, 12 (9): 1611–1614
34. Bao N Z, Shen L M, Takata T, Domen K, Gupta A, Yanagisawa K, Grimes C A. Facile Cd-thiourea complex thermolysis synthesis of phase-controlled CdS nanocrystals for photocatalytic hydrogen production under visible light. Journal of Physical Chemistry C, 2007, 111(47): 17527–17534
35. Borgarello E, Kalyanasundaram K, Gratzel M. Visible light induced generation of hydrogen from H_2S in CdS-dispersions, hole transfer catalysis by RuO_2. Helvetica Chimica Acta, 1982, 65(1): 243–248
36. Yang T T, Chen W T, Hsu Y J, Wei K H, Lin T Y, Lin T W. Interfacial charge carrier dynamics in core shell Au-CdS nanocrystals. Journal of Physical Chemistry C, 2010, 114(26): 11414–11420
37. Yang J H, Yan H J, Wang X L, Wen F Y, Wang Z J, Fan D Y, Shi J Y, Li C. Roles of cocatalysts in Pt-PdS/CdS with exceptionally high quantum efficiency for photocatalytic hydrogen production. Journal of Catalysis, 2012, 290: 151–157
38. Shangguan W F. Hydrogen evolution from water splitting on Nanocomposite photocatalysts. Science and Technology of Advanced Materials, 2007, 8(1,2): 76–81
39. Luo M, Liu Y, Hu J C, Liu H, Li J L. One-pot synthesis of CdS and Ni-doped CdS hollow spheres with enhanced photocatalytic activity and durability. ACS Applied Materials & Interfaces, 2012, 4(3): 1813–1821
40. Tabata M, Maeda K, Ishihara T, Minegishi T, Takata T, Domen K. Photocatalytic hydrogen evolution from water using copper gallium sulfide under visible-light irradiation. Journal of Physical Chemistry C, 2010, 114(25): 11215–11220
41. Zong X, Han J F, Ma G J, Yan H J, Wu G P, Li C. Photocatalytic H_2 evolution on CdS loaded with WS_2 as cocatalyst under visible light irradiation. Journal of Physical Chemistry C, 2011, 115(24): 12202–12208
42. Zong X, Wu G P, Yan H J, Ma G J, Shi J Y, Wen F Y, Wang L, Li C. Photocatalytic H_2 evolution on MoS_2/CdS catalysts under visible light irradiation. Journal of Physical Chemistry C, 2010, 114(4): 1963–1968
43. Sayama K, Mukasa K, Abe R, Abe Y, Arakawa H. Stoichiometric water splitting into H_2 and O_2 using a mixture of two different photocatalysts and IO_3^-/I^- shuttle redox mediator under visible light irradiation. Chemical Communications (Cambridge), 2001, (23): 2416–2417
44. Kato H, Hori M, Konta R, Shimodaira Y, Kudo A. Construction of Z-scheme type heterogeneous photocatalysis systems for water splitting into H_2 and O_2 under visible light irradiation. Chemistry Letters, 2004, 33(10): 1348–1349
45. Tada H, Mitsui T, Kiyonaga T, Akita T, Tanaka K. All-solid-state Z-scheme in CdS-Au-TiO2 three-component nanojunction system. Nature Materials, 2006, 5(10): 782–786
46. Shangguan W F, Yoshida A. Photocatalytic hydrogen evolution from water on nanocomposites incorporating cadmium sulfide into the interlayer. Journal of Physical Chemistry B, 2002, 106(47): 12227–12230
47. Sato T, Masaki K, Sato K, Fujishiro Y, Okuwaki A. Photocatalytic properties of layered hydrous titanium oxide/CdS-ZnS nanocomposites incorporating CdS-ZnS into the interlayer. Journal of Chemical Technology and Biotechnology (Oxford, Oxfordshire), 1996, 67(4): 339–344
48. Sato T, Sato K, Fujishiro Y, Yoshioka T, Okuwaki A. Photochemical reduction of nitrate to ammonia using layered hydrous Titanate/Cadmium sulphide nanocomposites. Journal of Chemical Technology and Biotechnology (Oxford, Oxfordshire), 1996, 67(4): 345–349
49. Shangguan W F, Yoshida A. Synthesis and photocatalytic properties of CdS-intercalated metal oxides. Solar Energy Materials and Solar Cells, 2001, 69(2): 189–194
50. Gao X F, Sun W T, Hu Z D, Ai G, Zhang Y L, Feng S, Li F, Peng L M. Hu Z-D, Ai G, Zhang Y-L, Feng S, Li F, Peng L-M. An efficient method to form heterojunction CdS/TiO_2 photoelectrodes using highly ordered TiO_2 nanotube array films. Journal of Physical Chemistry C, 2009, 113(47): 20481–20485
51. Barpuzary D, Khan Z, Vinothkumar N, De M, Qureshi M. Hierarchically grown urchinlike CdS@ZnO and CdS@Al_2O_3 heteroarrays for efficient visible-light-driven photocatalytic hydrogen generation. Journal of Physical Chemistry C, 2012, 116(1): 150–156
52. Wang L, Wei H W, Fan Y J, Gu X, Zhan J H. One-dimensional CdS/r-Fe_2O_3 and CdS/Fe_3O_4 heterostructures: epitaxial and nonepitaxial growth and photocatalytic activity. Journal of Physical Chemistry C, 2009, 113(32): 14119–14125
53. Li C L, Yuan J, Han B Y, Jiang L, Shangguan W F. TiO_2 Nanotubes incorporated with CdS for photocatalytic hydrogen production from splitting wat$_e$r under visible light irradiation. International Journal of Hydrogen Energy, 2010, 35(13): 7073–7079
54. Xing C J, Zhang Y J, Yan W, Guo L J. Band structure-controlled solid solution of $Cd_{1-x}Zn_xS$ photocatalyst for h$_y$drogen production by water splitting. International Journal of Hydrogen Energy, 2006, 31(14): 2018–2024
55. Kimi M, Yuliati L, Shamsuddin M. Photoca$_t$alytic hydrogen production under visible light over $Cd_{0.1}Sn_xZn_{09-2x}S$ solid solution photocatalysts. International Journal of Hydrogen Energy, 2011, 36 (16): 9453–9461
56. Ikeue K, Shiiba S, Machida M. Novel Visible-light-driven photocatalyst based on Mn-Cd-S for efficient H_2 evolution. Chemistry of Materials, 2010, 22(3): 743–745
57. Xie S L, Lu X H, Zhai T, Gan J Y, Li W, Xu M, Yu M H, Zhang Y M, Tong Y X. Controllable synthesis of $Zn_xCd_{1-x}S$@ZnO core-shell nanorods with enhanced photocatalytic activity. Langmuir, 2012, 28(28): 10558–10564
58. Zhang J, Yu J G, Jaroniec M, Gong J R. Noble metal-free reduced graphene oxide-ZnxCd$_{1-x}$S nanocomposite with enhanced solar photocatalytic H_2-production performance. Nano Letters, 2012, 12 (9): 4584–4589
59. Gao P, Liu J C, Lee S, Zhang T, Sun D D. High quality graphene

oxide-CdS-Pt nanocomposites for efficient photocatalytic hydrogen evolution. Journal of Materials Chemistry, 2012, 22(5): 2292–2298

60. Lee H, Heo K, Maaroof A, Park Y, Noh S, Park J, Jian J, Lee C, Seong M J, Hong S. High-performance photoconductive channels based on (carbon nanotube)-(CdS nanowire) hybrid nanostructures. Small, 2012, 8(11): 1650–1656
61. Jia L, Wang D H, Huang Y X, Xu A W, Yu H Q. Highly durable N-doped graphene/CdS nanocomposites with enhanced photocatalytic hydrogen evolution from water under visible light irradiation. Journal of Physical Chemistry C, 2011, 115(23): 11466–11473
62. Gao Z Y, Liu N, Wu D P, Tao W Q, Xu F, Jiang K. Graphene-CdS composite, synthesis and enhanced photocatalytic activity. Applied Surface Science, 2012, 258(7): 2473–2478