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A bifacial quantum dot-sensitized solar cell with all–cadmium sulfide photoanode

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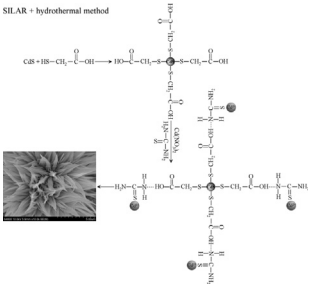
HIGHLIGHTS

- Bifacial QDSSCs from all-CdS photoanides are fabricated.
- Nanoflower-structured CdS QDs are synthesized by a hydrothermal process.
- A front efficiency of 1.67% and a rear efficiency of 1.17% are obtained for the QDSSC.

GRAPHICAL ABSTRACT



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ABSTRACT

Pursuit of a high power conversion efficiency and reduction of electricity-generation cost has been a persistent objective for quantum dot-sensitized solar cells (QDSSCs). We present here the fabrication of a QDSSC comprising a nanoflower-structured CdS anode, a liquid electrolyte having S^{2-}/S_n^{2-} redox couples, and a transparent CoSe counter electrode. Nanoflower-structured CdS anodes are prepared by a successive ionic layer adsorption and reaction (SILAR) method and subsequently hydrothermal strategy free of any surfactant or template. The CdS nanoparticles synthesized by a SILAR method act as "seed crystal" for growth of CdS nanoflowers. The average electron lifetime is markedly elevated in nanoflower-structured CdS anode in comparison with CdS nanoparticle or nanoporous CdS microsphere anode. Herein, we study the effect of synthesis method on CdS morphology and solar cell's photovoltaic performance, showing a power conversion efficiency of 1.67% and 1.17% for nanoflower-structured CdS QDSSC under front and rear irradiations, respectively.

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1. Introduction

In comparison with dye-sensitized solar cells [1,2], quantum dot-sensitized solar cells (QDSSCs) [3–7] have attracted considerable attention due to their merits on high theoretical power conversion efficiency (the quantum dots can absorb each photon and release multiple electrons), low fabrication cost, and good extinction coefficient. Since quantum dots have a large surface to volume

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ratio, defect states at the surface are one of the causes of charge trapping [8]. This largely affects the performance of the devices confining the power conversion efficiency of CdS QDSSCs made by a successive ionic layer adsorption and reaction (SILAR) to below 2% [9,10]. Only the combination of CdS with other metal sulfite quantum dots results in device efficiencies of above 5% [11–13]. However, relatively complicated process indeed increase the fabrication cost.

Hydrothermal technique is a promising strategy in fabricating versatile inorganic semiconductors [14], not only inducing the formation of well-crystallized nanocrystals at low temperature but also controlling the size and shape of the nanocrystals. Multiple morphological semiconductors such as nanowires [15], nanorods [16], nanotubes [17], nanoflowers [18] et al. have been successfully achieved for semiconductor materials. More importantly, the semiconductor nanostructures are expected to have good crystallization and less defects, which elevate the solar cell performances. Additionally, a bifacial technique developed by Grätzel is considered as an efficient approach in elevating electricity generation and bringing down the cost of solar energy production [19,20]. A remaining problem in designing robust bifacial QDSSCs is to enhance light penetration from read side (counter electrode side). Metal sulfides or carbon supported metal sulfides are always employed as CE materials for QDSSCs [21,22], the colored and semitransparent nature of metal sulfides generates a low light transmission for incident light, and therefore relatively low illumination and excitation of CdS quantum dots.

The responsibility of a photoanode is to enhance light harvesting [23–25], to upload photosensitizers, and to conduct photogenerated electrons along conducting channels, in this fashion, we pioneerly synthesize CdS quantum dots by a SILAR method and subsequently mild hydrothermal process which are assembled into a bifacial QDSSC device using transparent CoSe counter electrode. The aim of the original intension is to decrease crystal defects and to enhance rear efficiency. Before the hydrothermal growth, CdS seeds are adsorbed onto TiO_2 nanocrystallites by repeating in-situ deposition of Cd and S sources. The resultant bifacial QDSSC yields the maximum front efficiency of 1.67% and rear efficiency of 1.17% are achieved under one sun irradiation, which is higher than the solar cells with SILAR-only prepared CdS nanoparticle anode or cell with nanoporous CdS microsphere anode by a hydrothermal method.

2. Experimental

2.1. Fabrication of photoanodes

FTO glass substrates (sheet resistance 12 Ω sq^{-1}, purchased from Hartford Glass Co., USA) with a size of 2 × 2 cm^2 were thoroughly rinsed by deionized water and anhydrous ethanol, and dried by N_2 gas flow. The photoanodes for QDSSC application were fabrication by three avenues. (i) SILAR [19]: The freshly cleaned FTO glass was immersed into 0.1 M cadmium acetate ethanol solution for 1 min, rinsed with anhydrous ethanol and dried by N_2 gas stream, then immersed in 0.02 M Na_2S methanol solution for 1 min. After being vacuum dried at 60 °C, the substrate was immersed into 0.02 M $Cd(NO_3)_2$ ethanol solution for 1 min, rinsed with anhydrous ethanol and dried by N_2 gas stream, then immersed in 0.02 M Na_2S methanol solution for 1 min and rinsed with anhydrous methanol and dried by N_2 gas. By repeating the previous procedures for 20 cycles, we could obtain CdS anodes by a SILAR method. (ii) SILAR and hydrothermal: The FTO glass supported CdS synthesized by route (i) with FTO layer downward was transferred into a Teflon-lined autoclave, the autoclave was 50 mL of 2 mM $Cd(NO_3)_2$ and 24 mM sulfocarbamide aqueous solutions, and 0.2 mL thioglycolic acid. After the reaction at 120 °C for 12 h, the substrate was rinsed by deionized water and vacuum dried at 50 °C. (iii) Hydrothermal: The cleaned FTO glass with FTO layer downward was put in a Teflon-lined autoclave, the autoclave was 50 mL of 20 mM $Cd(NO_3)_2$ and 240 mM sulfocarbamide aqueous solutions, and 0.2 mL thioglycolic acid. After the reaction at 120 °C for 12 h, the substrate was rinsed by deionized water and vacuum dried at 50 °C.

2.2. Preparation of binary CoSe alloy CEs

The feasibility of this strategy was confirmed by following experimental procedures: A mixing aqueous solution consisting of

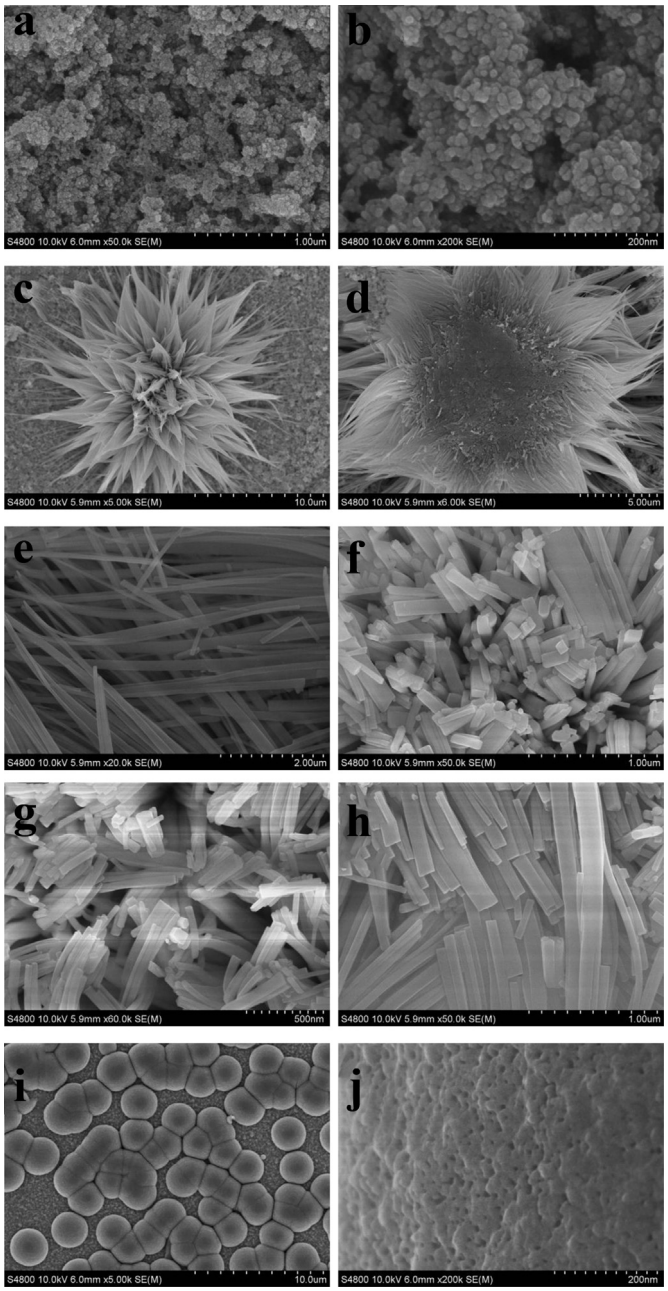

Fig. 1. Top-view SEM images of CdS photoanodes: (a)&(b) CdS nanoparticles by route (i); (c) CdS nanoflower by route (ii) at a reaction time of 12 h; (d) CdS nanoflower by route (ii) at a reaction time of 6 h; (e) "Leaves" of CdS nanoflower for image (c); "Pistil" of CdS nanoflower at a reaction time of (f) 3 h, (g) 6 h, and (h) 12 h; Porous CdS microspheres by route (iii) at (i) low and (j) high magnifications.

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