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Enhanced synthesis of cadmium sulfide by electrodeposition in dye-sensitized solar cells

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ABSTRACT

Cadmium sulfide thin film (CdS_{TF}) and cadmium sulfide nanoparticles (CdS_{NPs}) were fabricated by using a simple electrodeposition (ECD) and chemical bath deposition (CBD) respectively. The morphology, phase composition, and structure were investigated by employing scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD). Their optical absorption capability and the electrical properties were also studied. The organic/inorganic hybrid solar cell devices were fabricated based on CdS_{TF} and CdS_{NPs} with poly(3,4-ethylenedioxyl-thiophene)/poly (styrene-sulfonate) (PEDOT:PSS). CdS_{TF} has the potential for enhanced the performance in dye-sensitized solar cells (DSSCs) due to its improvable charge carrier collection. The experimental results showed the improved efficiency in cadmium sulfide thin film with titanium dioxide (CdS_{TF}-TiO_2) has reached 2.7%. This is much better than (CdS_{NPs}-TiO_2) with efficiency 0.86% under similar conditions. This study demonstrates that electrodeposition is a promising technique for large-scale fabrication, of CdS_{TF}, in DSSCs.

1. Introduction

The DSSC technique is widely recognized to be a cost-effective method to make effective photovoltaic devices. Graetzel et al. were the first producers of the DSSC devices, which generated a broad interest for both academics and industrial communities. Comparing to the conventional silicon solar cells, DDSCs are inexpensive and easier to fabricate. In addition, DSSC solar cells can be made to have high conversion efficiency (above 10%), yet have a much low production cost (Bin Ahmad and Murakami, 2011). DSSCs are inexpensive to fabricate because they have some exceptional features such as: (1) They can be processed at ambient temperature; (2) the resultant DSSCs is especially well suited for dawn, dusk, or cloudy low-light conditions, because diffused light does not reduce their efficiency, thus DSSCs are very useful for indoors usage (Gong et al., 2017). In addition, they are insensitivity to environmental contaminant. Their interesting physical properties and potential uses in the form of semiconducting nanoparticles make them a significant category of constituent materials solar cells and other devices (Alivisatos, 1996; Prabhu and Khadar, 2008).

Due to their usefulness in semiconductor electronics and optical devices, nanostructural metal chalcogenides, such as PbS, ZnS, CdS, CdTe, CdSe, Ag_2S, and the co-sensitized CdS/CdSe are subjected to significant attention (Holi and et al., 2016). CdS nanoparticles are under a great deal of research because of its easiness in synthesis and has a tunable wavelength (Lane et al., 2009; Harru and Bunker, 2003). CdS along with CdSe, CdTe, and PbS particles have been the materials under most active research and discussions in the literature especially in the field of nano-electronics and solar cells (Lane et al., 2009; Vogel et al., 1994; Gao et al., 2009; Robel et al., 2006).

The compound CdS has a wide applications in photo-sensors, photovoltaics devices, and solar cells (Mohammed et al., 2016). The advantages of CdS include high optical absorption, high reflectance in the infrared region and high transmittance in the visible region, superior electron affinity, easy in making ohmic contact, and low resistivity. The compound is an n-type semiconductor with a 2.42 eV direct band gap when it is in cubic structure, and 2.57 eV when it is in hexagonal structure. CdS has a Bohr radius of 2.4 nm (Xiong et al., 2010). Electrical short circuit effects can be avoided in CdS thin films solar cell by making the film thicker. Its electric conductivity is greater than 10^{16} carriers/cm^3. These features allow the films to grow with good uniformity and high transmission.

The properties of a CdS film depend very much on the specific conditions and methods used to prepare the film. Preparation can be via physical, electrochemical, and chemical approaches. Among the fabrication techniques for CdS thin film are molecular beam epitaxy (MBE) (Armstrong, 2014; Alkuam et al., 2017), successive ionic layer

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adsorption and reaction (SILAR), spray pyrolysis, metal organic chemical vapor deposition (MOCVD), chemical bath deposition (CBD) (Mondal et al., 1983; Oliva et al., 2003; Armstrong, 2014), electrodeposition, spin coating, pulsed laser ablation, screen printing, close-spaced sublimation (Oliva et al., 2003), and RF sputtering (Alkuam et al., 2017; Prasad et al., 2016).

The predominant semiconductor oxide in DSSCs studies is the titanium dioxide (TiO_2), largely because of its desirable band gap and its easiness to be processed into thin films for electronics. TiO_2 is a semiconductor, but is a very common base used for paint manufacturing; the needed dye sensitizer can be economically extracted from a wide range of natural sources. TiO_2 has an extremely porous three-dimensional structure, which makes it a good fit to a large variety of sensitizing agents for fabricating DSSCs (Lane et al., 2009). In DSSCs carbon nanotubes and organic materials have been used to reduce expenses in the manufacturing process of solar cells. They were used as a counter electrode instead of platinum in DSSCs. The resultant DSSCs is especially well suited for dawn, dusk, or cloudy low-light conditions. Because diffused lighting does not reduce the efficiency, thus DSSCs are useful for usage indoors (AbdulAlmohsin et al., 2012; Mohammed et al., 2014).

In this article, DSSCs were synthesized by using TiO_2 coated CdS_{TF} or CdS_{NPs} fabricated through electrochemical and chemical bath technique to produce the n-type semiconductor while the conductive polymer PEDOT:PSS was used as p-type because it has high conductivity and it is widely available. The PEDOT:PSS was prepared via spin coating. Solution casting and spin coating are the two easiest dispersion means for producing PEDOT:PSS (Yan et al., 2009). 2.7% conversion efficiency was obtained for CdS_{TF} while that for CdS_{NPs} is only 0.86%. Morphological structural, optical, and electrical properties of the fabricated devices were also investigated in this research.

2. Experiments

2.1. Chemicals and materials

The chemicals: thioacetimide ≥99.4%, potassium iodide KI, dimethyl sulfoxide, ethanol, acetic acid and acetone were purchased from Fisher Scientific; while cadmium acetate ≥98.0%, sulfur powder, precipitated 99.5%, were purchased from Alfa Easar; Di-tetrabutylammonium *cis*-bis(isothiocyanato)bis (2,2-bipyridyl-4,4-dicarboxylato) ruthenium(II) (N-719 organometallic dye) 95%, ethylene glycol, titanium(IV) oxide anatase 99.7%, poly(3,4-ethylenedioxyl-thiophene)/poly(styrene-sulfonate) PEDOT:PSS, were purchased from Sigma Aldrich; iodine I_2 was from Mallinckodi Chemical Work and cadmium chloride $CdCl_2$ was from Acros Organics. Diethylzinc, Trimethylaluminum, and water (H_2O) were used as the basic precursors to grow aluminum doped zinc oxide (AZO), they were obtained from Stream Chemicals. Fluorine doped tin oxide (FTO) coated glass substrate, with a resistivity of 12–17 Ω cm was used as an electrode, and was purchased from Nanocs. All the chemicals were used as received without further purification.

2.2. Preparation of AZO

AZO was grown by atomic layer deposition (ALD) technique. Diethylzinc (DEZ), trimethylaluminium and distilled water vapor were used as the basic precursors to grow AZO on cleaned FTO. Then the FTO was employed as an electrode, which was ultrasonically cleaned by acetone, methanol and deionized water for 10 min each, and finally dried by blowing nitrogen gas. The selected substrates were placed in Cambridge Nanotech Fiji F200 ALD reactor. The deposition of AZO was in the chamber at 200 °C process temperature and 750 mTorr argon (Ar) pressure. High purity Ar was used as the process gas. A DEZ and H_2O pulses briefly increased the pressure by 30–40 mTorr. The process was repeated for 18 cycles leading to a highest conducting AZO film of thickness 80 nm.

2.3. Preparation of CdS precursors

Two precursors of CdS were prepared by electrochemical and chemical bath techniques.

The CdS_{TF} were deposited on AZO/FTO by electrochemical deposition to produce the first precursor 0.055 M and 0.19 M from cadmium chloride and sulfur were dissolved in dimethyl sulfoxide and stir for 30 min, then the solutions was mixed together until a clear solution is achieved, electrolysis was occurred at current (2–3) mA with a −3 V external voltage. The deposition occurred in the electrolyte solution at 120 °C and the solution was stirred by using a magnetic stirrer at 120 rpm during the deposition (Fatas et al., 1987).

Ammonia free chemical bath has been used for the precursor deposition on AZO/FTO, where 0.0001 M and 0.0002 M from cadmium acetate and thioacetimide respectively were dissolved in deionized water to prepare a second precursor solution for CdS using chemical bath deposition. The deposition was carried out at 80 °C for 80 min and the solution was stirred during the growth of CdS_{NPs} (Choi et al., 1998). CdS_{NPs} were produced through the reactions between Cd^{-2} an S^{+2} ions in a slightly acidic or neutral solution with pH from 6 to 7 (DissertationChapter 1 v_01 3-7-2014-2).

2.4. Preparation of TiO_2, dye N719 and PEDOT:PSS

The solution needed to prepare TiO_2 is obtained by mixing 6 g of TiO_2 nanopowder with acetic acid, and DI water (15%: 75%) and ultrasonically dispersed for 30 min. Then the mixture was deposited by using airbrush technique to produce a dense layer of TiO_2 onto FTO/AZO/CdS_{NPs} and FTO/AZO/CdS_{TF}. They were subsequently annealed in the oven at 450 °C for 30 min to enhance the crystal size. Finally, the resultant TiO_2 layer was immersed in a dye bath, which was prepared by dissolving 0.01 g of the dye in 20 ml ethanol, where the concentration of dye is (0.5 g/L). The samples were left in a dye bath for about 18 h to get a FTO/AZO/CdS_{TF}-TiO_2/N719 working electrode.

The high-conductivity PEDOT:PSS films were prepared using a two-step method. First the PEDOT:PSS was filtered through a 0.45 mm filter and ethanol was added to the PEDOT:PSS with a ratio 1:3 to enhance the conductivity (Yan et al., 2009; Choudhury et al., 2011; Hsiao et al., 2008), then deposited onto cleaned FTO with a surface area of 1.5 cm^2 at a thickness ~2 μm through spin-coating at 4500 rpm and dried at 150 °C for 10 min in the air on a hot plate.

2.5. Solar cell fabrication

To fabricate the solar cell, few drops of the electrolyte were adding on the top of FTO/AZO/CdS_{TF}-TiO_2/N719 and PEDOT:PSS/FTO, the electrolyte solution was prepared by utilizing 0.127 g of I_2, and 0.83 g of KI dissolved in 10 ml ethylene glycol. Then sandwich both electrodes to fabricate the photovoltaic device DSSCs, by using binder clips.

The schematic diagram of FTO/AZO/CdS_{TF}-TiO_2/PEDOT:PSS/FTO is shown in Fig. 1.

3. Characterization

Scanning electron microscopy (SEM, JEOL JSM7000F) with energy dispersive X-ray analysis (EDX) was used to characterize the samples by observation surface morphologies and the composition. The crystal structure of the synthesized CdS_{TF} and CdS_{NPs} were determined by X-ray diffraction (XRD) patterns by a Rigaku Miniflex 600 X-ray diffractometer with copper target; the wavelength of the CuK radiation is 1.54056 Å. The optical absorbance was measured using a UV–visible spectrometer. A Keithley 2400 source was used to measure and record the current-voltage (I-V) characteristics.