Physica E: Low-dimensional Systems and Nanostructures

Volume 144, October 2022, 115469

Optimizing the size and amount of CdS quantum dots for efficiency enhancement in CdS/N719 co-sensitized solar cells

M.A.K.L.Dissanayake

T.Jaseetharan

G.K.R.Senadeera

B.E.Mellander

I. Albinsson

M.Furlani

https://doi.org/10.1016/j.physe.2022.115469

Abstract

Co-sensitization of TiO_2 photoanodes in solar cells with Ruthenium dye and quantum dots offer better photovoltaic performance compared to the sensitization by the dye only. In the present study, TiO_2 nanostructured photoanode was co-sensitized with CdS quantum dots and N719 dye. CdS quantum dots were deposited using successive ionic layer adsorption and reaction (SILAR). A suitable thin ZnS interfacial layer has been introduced between two sensitizers to prevent the corrosion of CdS quantum dots by the iodide-based liquid electrolyte. In order to get the highest efficiency, the number of SILAR cycles for CdS quantum dot deposition has been optimized.

A power conversion efficiency of 6.79% with short-circuit current density of 15.55 mA cm^{-2} and open circuit voltage of 764.5 mV have been obtained for the co-sensitized solar cell made with TiO_2/CdS/ZnS/N719 co-sensitized photoanode under the illumination of 100 mW cm^{-2} with AM 1.5 spectral filter. Efficiency and short-circuit current density of the solar cell have been enhanced by 11.31% and 6.58% respectively due to the co-sensitization. The optimized co-sensitized solar cell shows a higher incident photon to current conversion efficiency and a reduced electron recombination compared to the solar cell with dye-sensitized photoanode. Higher recombination resistance and longer electron lifetime of the solar cell with CdS/ZnS/N719 co-sensitized TiO_2 photoanode have contributed to the increased short circuit current and open circuit voltage leading to the enhanced efficiency of 6.79% which is among the highest for a co-sensitized dye sensitized solar cell.

Introduction

Dye-sensitized solar cells (DSSCs) are a promising class of devices for solar energy conversion applications. In these solar cells, Ruthenium-based dyes are commonly used to sensitize the TiO_2 photoanode. These dyes show broad absorption in the visible region of the solar spectrum. However, one dye molecule can create only one electron-hole pair from one photon whereas one semiconductor quantum dot can create more than one electron-hole pairs due to the ability of multiple exciton generation. Semiconductor quantum dots have attracted extensive attention over the past decades with different applications including light emitting diodes [[1], [2], [3]], photodetectors [[4], [5], [6]], transistors [7,8], spectrometers [9,10] and solar cells [[11], [12], [13]] due to their unique size dependent optoelectronic properties [14,15]. Quantum dot-sensitized solar cells have gained more attention in the area of solar energy conversion systems due to their low production cost and the excellent properties such as the ability of multiple exciton generation and high molar extinction coefficients [[16], [17], [18]].

Jing Li et al. reported dye-sensitized solar cells co-sensitized by CdS quantum dots and N719 with an efficiency of 5.57% [19]. Recently, co-sensitization of TiO_2 by PbS quantum dots and N719 has been reported with an efficiency of 6.35% by Yanqiong Liu et al. [20]. Subramaniam et al. reported CdSe quantum dots and N719 co-sensitized hierarchical TiO_2 nanorod based co-sensitized solar cell with an efficiency of 3.93% [21]. In another related study, Meng et al. [22] reported CdS/N719 co-sensitized solar cell with an efficiency of 3.93%. In addition to the CdS quantum dots, carbon quantum dots and doped quantum wells have been studied recently in the solar energy conversion process. $CsPb(Br_xI_{1-x})_3$ quantum dots and $CsPb(Cl_xBr_{1-x})_3$ quantum dots show better photostability and absorption in ultraviolet region [23]. Haiguang Zhao et al. reported Cs_4PbBr_6 quantum dot based solar cells with a power conversion efficiency of 1.8% under the natural sun illumination (30 mW cm^{-2}) [24]. Haiguang Zhao et al. reported the eco-friendly and high efficiency solar concentrators with carbon quantum dots popularly known as “green quantum dots” [25]. Vertically aligned ZnO nanowires-based CdTe quantum dots and dye solar cells have been reported [26]. Recently, organic solar cell has been reported by Zhang et al. with simultaneously enhanced photocurrent and open circuit voltage medium-band gap acceptor [27]. Haung et al. reported the effect of ZnSe passivation layer on the performance of CdS/CdSe quantum dot sensitized solar cells [28]. High efficiency CdS/CdSe quantum dot-sensitized solar cells with two ZnSe layers with an efficiency of 7.24% [29].

Number of dye molecules on TiO_2 nanoporous electrode also determines the efficiency of the solar cell. Usually, monolayer of dye molecules is better to give high efficiency. If we increase the number of dye molecules, they form multilayers on the TiO_2 nanostructure. If we use another type of sensitizer with different absorption region, the performance of the cell can be enhanced. In the present study, TiO_2 photoanode nanostructure was co-sensitized with CdS quantum dots and N719 dye. In order to achieve a higher efficiency, the number of cycles used for deposition of CdS by SILAR method was optimized using I–V measurements on trial solar cells. Both, the

iodide/triiodide redox couple as well as the polysulfide electrolyte is compatible with N719 dye and quantum dots. However, in the presence of the polysulfide electrolyte, regeneration of dye molecules is very poor. Therefore, iodide-based electrolytes are better to be used in co-sensitized solar cells. In this case, again, quantum dots are corroded by iodide electrolytes and a possible strategy to overcome this is to isolate the CdS quantum dots by a thin semiconductor layer of a different material, such as ZnS with a suitable thickness. By this way, we have been able to fabricate and characterize highly efficient, CdS/N719 co-sensitized solar cells.

Fig. 1 shows the schematic energy level diagram of TiO_2/CdS/ZnS/N719 co-sensitized photoanode. Conduction band of TiO_2 is slightly lower than that of CdS quantum dots which enables the efficient electron injection. Conduction band edge of CdS quantum dot is lower than the lowest unoccupied molecular orbit (LUMO) of N719 dye molecule. It can be seen that, the photo-generated electrons in N719 dye molecules can easily transferred to the conduction band of TiO_2. ZnS passivation layer prevents the electron transfer back reaction from the CdS quantum dots and TiO_2 photoanode to the electrolyte. Highest occupied molecular orbital (HOMO) of N719 dye is higher than the edge of the valence band of CdS and TiO_2. Therefore, N719 acts as a hole scavenger for the CdS quantum dots in addition to the sensitization [30,31]. In this work, iodide-based redox couple was used as the electrolyte. In order to prevent the corrosion of CdS quantum dots, a narrow ZnS passivation layer was deposited between the CdS quantum dots and the N719 dye. In this study, ZnS deposition with 2 SILAR cycles gives the best efficiency for the CdS/ZnS/N719 co-sensitized solar cell. The presence of a narrow ZnS layer acts as a dielectric layer between the CdS layer and the N719 dye molecules and facilitate the effective charge transfer [31]. Optimized thickness of the ZnS passivation layer protects the CdS quantum dots from iodide-based electrolyte without affecting the photoinduced electron transfer.