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Enhanced performance of cadmium selenide quantum dot-sensitized solar cells by incorporating long afterglow europium, dysprosium co-doped strontium aluminate phosphors

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ABSTRACT

CdSe quantum dot-sensitized solar cells based on an efficient bifunctional structured layer composed of long afterglow $SrAl_2O_4$:Eu,Dy phosphors on top of a transparent layer of nanocrystalline TiO_2 were fabricated and their photovoltaic performances were investigated. The results show that a high power conversion efficiency of 1.22% is achieved for the cell with $SrAl_2O_4$:Eu,Dy at one sun illumination (AM 1.5 G, 100 mW cm^{-2}), which is an increase of 48% compared to the cell without $SrAl_2O_4$:Eu,Dy (0.82%). After one sun illumination for 1 min and subsequent turn off of the light source, the cell with $SrAl_2O_4$:Eu,Dy still shows an efficiency of 0.04% under dark condition due to the irradiation by the long persistent light from $SrAl_2O_4$:Eu,Dy. The present strategy should provide a possibility to fulfill the operation of solar cells even in the dark.

1. Introduction

Currently dye-sensitized solar cells (DSSCs) have attracted much attention for their practical application as a promising candidate for the development of next generation solar cells because of their low fabrication cost and relatively high efficiency [1–7]. In recent years, inorganic quantum dots (QDs), typically CdS or CdSe, have also been employed as sensitizers due to their larger absorption coefficients and the tunability of their absorption spectra by quantum size confinement [8–11].

In quantum-dot sensitized solar cells (QDSSCs), the light harvesting ability of photoanode is one of the key issues for device performance [12–16]. Researchers have attempted to enhance the light harvesting by employing an efficient light scattering layer on the photoanode to localize the incident light within the photoanode and increase the light absorption [17–19]. Recently, another attractive strategy to improve the light harvesting is explored by introducing light-converting materials including up-converting and down-converting materials into photoanode [20–22]. These light-converting materials can transform lower (higher) energy photons into high (low)-energy visible photons that are easily absorbed by the sensitizer [23–26]. In our previous work, a novel structure consisting of long afterglow $SrAl_2O_4$:Eu,Dy phosphors on top of TiO_2 layer was used in CdS QDSSCs, offering both light scattering and light down-converting properties. A power conversion efficiency of 1.24%, 26.5% higher than that of the cell without $SrAl_2O_4$:Eu,Dy, was achieved [27]. However, due to the band gap (2.4 eV) of CdS QDs, only part of the emitted light from $SrAl_2O_4$:Eu,Dy could be absorbed by CdS QDs. The enhanced cell efficiency was mainly resulted from the improved light scattering and the contribution from light down-converting was relatively not obvious. As compared with CdS, CdSe with a more narrow band gap (1.7 eV) can absorb the light with a wider wavelength range and should be an ideal sensitizer for the down-converting light from $SrAl_2O_4$:Eu,Dy [28–30].

In this work, we further studied the application of long afterglow $SrAl_2O_4$:Eu,Dy phosphors as efficient bifunctional structure layer in the photoanode of CdSe QDSSCs. The cell with $SrAl_2O_4$:Eu,Dy shows a conversion efficiency of 1.22% under one sun illumination, which is an increase of 48% compared with the cell without it (0.82%). The IPCE is also enhanced with two peak values at 350 and 500 nm, corresponding to the contributions of light down-converting and light scattering from $SrAl_2O_4$:Eu,Dy, respectively. Due to the irradiation by the long persistent light from $SrAl_2O_4$:Eu,Dy [31], the cell with $SrAl_2O_4$:Eu,Dy can still be driven even if the light source is turned off after illumination.

2. Experimental

TiO_2 nanoparticle film electrodes were prepared by screen printing of P25 with a mean size of 25 nm on F-doped SnO_2 (FTO) glass (resistivity: 14 Ω/□, Nippon Sheet Glass, Japan). Subsequently, the $SrAl_2O_4$:Eu,Dy phosphors (Jinan Xingyue LED Technol-

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ogy Co., Ltd.) were deposited on top of TiO_2 film layer by screen printing method. The as-prepared electrodes were sintered at 500 °C for 30 min.

The as-prepared electrodes were sensitized by CdSe QDs using microwave-assisted chemical bath deposition method as reported in our previous work [28]. In brief, Se powder (32 mg) was added to a mixture of 10 ml 0.04 M $Cd(NO_3)_2$ and 10 ml 0.04 M Na_2SO_3 (Sinopharm Chemical Reagents Co., Ltd.) as a precursor aqueous solution. The TiO_2 electrodes were immersed in a vessel with the precursor aqueous solution, and then the vessel was put into an automated focused microwave system (Explorer-48, CEM Co.) and treated at 150 °C with a microwave irradiation power of 100 W for 20 min.

The CdSe QDSSCs were sealed in a sandwich structure with a 60 μm spacer (Surlyn) by using thin Pt counter electrode. The redox electrolyte was composed of 0.5 M Na_2S, 2 M S, and 0.2 M KCl in a solvent mixture of 70% methanol with 30% water by volume [32]. The active area of the cells is 0.2 cm^2. The structure and working mechanism of CdSe QDSSCs are depicted in Fig. 1, involving the key processes (1)–(7). In brief, electrons, excited from the valance band (VB) to the conduction band (CB) of the CdSe QDs by absorbing light (path (1)), are rapidly injected into the CB of the TiO_2 particles (path (2)) and then transported to the F-doped SnO_2 (FTO) (path (3)). The oxidized QDs are regenerated by accepting the electrons from a counter electrode (CE) (path (5)) via a redox pair (path (4)). However, the charge recombination (paths (6) and (7)) will happen in the meantime and deteriorate the cell performance.

Photocurrent–voltage (J–V) measurement was performed with a Keithley model 2440 Source Meter and a Newport solar simulator system (equipped with a 1 kW xenon arc lamp, Oriel) under one sun illumination (AM 1.5G, 100 mW cm^{-2}). Incident photon to current conversion efficiency (IPCE) was measured as a function of wavelength from 300 to 800 nm using an Oriel 300 W xenon arc lamp and a lock-in amplifier M 70104 (Oriel) under monochromator illumination.

3. Results and discussion

The morphology and structure of the electrodes were characterized by using a Hitachi S-4800 field emission scanning electron

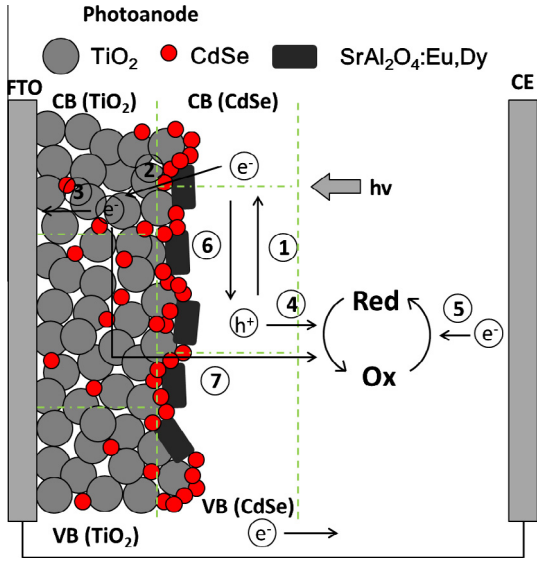

Fig. 1. Schematic diagram of the structure and working mechanism of CdSe QDSSCs with P25/$SrAl_2O_4$:Eu,Dy/CdSe electrode.

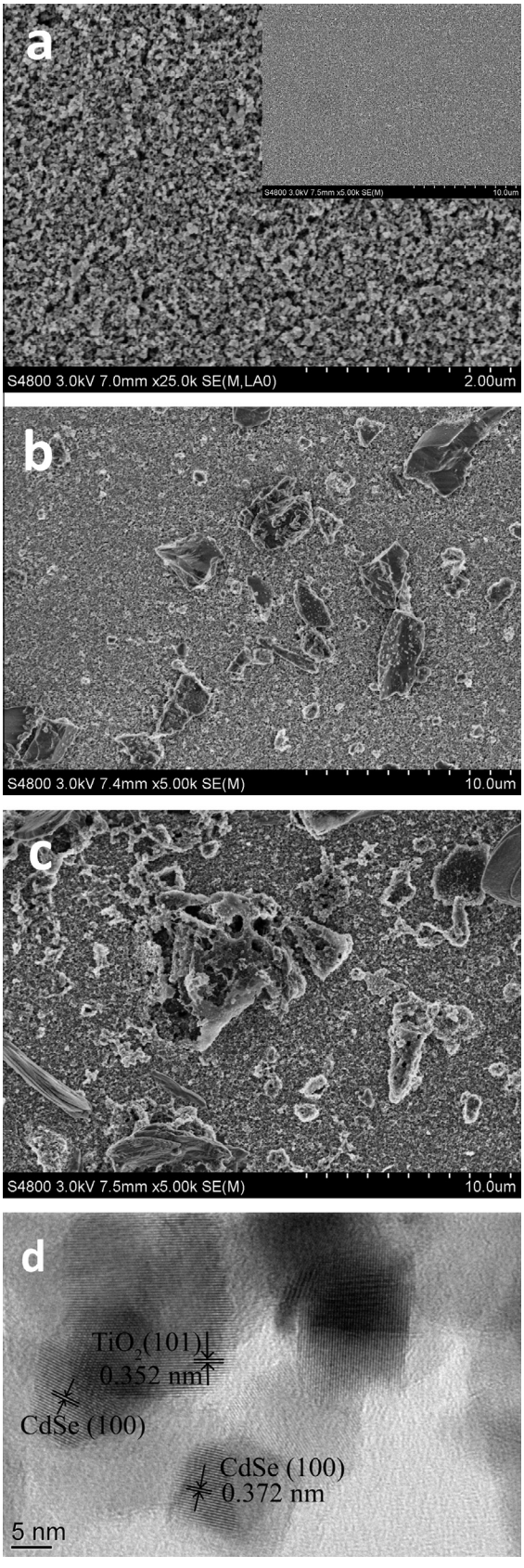

Fig. 2. Surface morphologies of (a) P25 (inset is the low magnification image), (b) P25/$SrAl_2O_4$:Eu,Dy, (c) P25/$SrAl_2O_4$:Eu,Dy/CdSe electrodes measured by FESEM, and (d) high-magnification HRTEM image of P25/CdSe electrode.