Solar Energy Materials & Solar Cells 95 (2011) 2874–2879

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

A hybridized electron-selective layer using Sb-doped SnO_2 nanowires for efficient inverted polymer solar cells

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ARTICLE INFO

Article history:
Received 14 February 2011
Received in revised form
27 May 2011
Accepted 4 June 2011
Available online 22 June 2011

Keywords:
Sb-doped SnO_2
1-D nanostructures
Nanowires
Electron-selective layers
Inverted polymer solar cells

ABSTRACT

We developed a novel hybridized electron-selective layer comprised of Sb-doped SnO_2 nanowires for efficient inverted polymer solar cells. A device containing Sb-doped SnO_2 nanowires with 0.1 mg/ml concentration showed a significant increase in power conversion efficiency to 3.23% with an enhanced fill factor, compared to a reference device without the nanowires (2.89%). Such improvement is attributed to the high electrical conductivity of one-dimensional Sb-doped SnO_2 nanowires and to the good light transmittance through the wide band gap of tin oxide. Also the surface morphology of the hybridized electron-selective layer is made denser and improved by incorporating one-dimensional Sb-doped SnO_2 nanowires, resulting in the enhancement of the photovoltaic performance.

1. Introduction

Inverted polymer solar cells (inverted-PSCs) have been considered as attractive photovoltaic devices because of the advantages they offer, such as high stability [1–3] and large-scale cell fabrication using ITO-free electrode and non-toxic solvent [4–10]. One of the critical factors in enhancing the photovoltaic performance of inverted-PSCs is the development of efficient electron-selective layers to facilitate electron transport and to have good light transmittance onto the cathode [11–13]. As a part of these efforts, ZnO nanoparticles have been developed into electron-selective layers and the beneficial effect of an annealed Cs_2CO_3 layer has been reported for electron-injection materials [14,15]. The morphology of ZnO has also been modified from a thin film to nano-ridges by a controlled annealing process [16].

Since one-dimensional (1-D) nanostructures, such as nanowires or nanotubes, are widely known for their outstanding electrical conductivity and optical properties [17], the use of 1-D nanostructures in photovoltaic cells can enhance charge transport properties by providing direct pathways of charges along their anisotropic morphologies [18–24]. Vertically aligned ZnO nanowires have been used as photoanodes in dye-sensitized solar cells and CdSe nanorods have been employed as n-type electron acceptors for hybrid solar cells to improve their electron transport properties [22,23]. Electrospun TiO_2 nanowires with a conjugated polymer have also been demonstrated to be an efficient electron-acceptor material with enhanced charge collection and transport properties in organic–inorganic hybrid solar cells [24]. Accordingly the implementation of 1-D nanostructure material would be of interest for use in electron-selective layers of inverted-PSCs because the electrons are likely to be transported to the cathode of inverted-PSCs through the 1-D nanostructures, thus reducing the recombination of charges and improving the photovoltaic performance of inverted-PSCs.

We synthesized Sb-doped SnO_2 nanowires (ATO NWs) by a simple one-pot electrospinning method. The ATO NWs, which had been applied to fuel cell electrodes with enhanced electron transport properties derived from high electrical conductivity [25], can be employed as electron-selective layers of inverted-PSCs because of their outstanding electrical conductivity and good light transmittance through transparent, electrically conducting, n-type oxide materials with a wide energy band gap (*ca.* 3.8 eV) [26–28]. In this work ATO NWs were employed, for the first time, in a sol–gel-processed ZnO thin film to enhance electron transport and to mitigate the recombination of charges over the electron-selective layers of inverted-PSCs. Our hybridized electron-selective layer containing the ATO NWs shows an improved photovoltaic performance, compared to ZnO thin film without the ATO NWs.

2. Material and methods

2.1. Synthesis of ATO NWs by electrospinning

To prepare Sb-doped SnO_2 nanowires using the one-pot electrospinning method, a precursor solution consisting of 0.1 g

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doi:10.1016/j.solmat.2011.06.004

of $SnCl_2 \cdot 2H_2O$ (at least 99.995%) and 0.018 g of $SbCl_3 \cdot 2H_2O$ (at least 99%) was mixed with 0.3 g of poly(vinyl pyrrolidone) (PVP, Mw = 1,300,000 g/mol) dissolved in 8 ml of methanol. The nominal molar ratio of Sn:Sb was controlled to 85:15. All chemicals were purchased from Aldrich Co. and used as received without further purification. After the solution was loaded into a syringe, the solution was ejected at the rate of 1.0 ml/h toward a vertically placed Si collector that was 10 cm away from the syringe needle. When a high potential of 9.5 kV was applied to the syringe needle, the precursor/PVP nanofibers were electrospun and collected on the Si collector. The as-spun nanofibers were calcined at 600 °C for 6 h in air to remove the organic material and produce the Sb-doped SnO_2 nanowires.

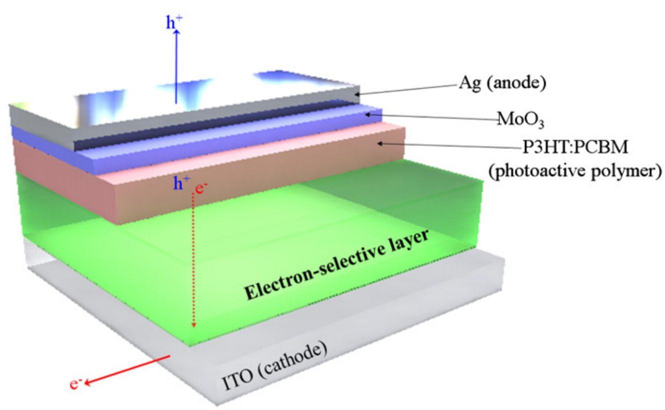

Fig. 1. Schematic illustration of inverted polymer solar cell as a reference device.

2.2. Characterization of structural properties of ATO NWs

The microstructure of the ATO NWs was investigated by scanning electron microscopy (SEM, JEOL-JSN7500F) and transmission electron microscopy (TEM, JEOL-2100). X-ray diffraction (XRD, Rigaku Rotalflex RU-200B) was performed with a Cu Kα source (λ = 1.5405 Å) to obtain the crystalline patterns of the NWs. X-ray absorption near-edge spectroscopy (XANES) was conducted at the 3C1 beamlines of the Pohang Accelerator Laboratory (PAL; 2.5 GeV with stored currents of 130–180 mA) in Korea to evaluate the antimony phase in the ATO NWs. A Si (1 1 1) double crystal monochromator was employed to monochromatize the X-ray photon energy. The XANES spectra were taken in transmission mode for the K-edge of Sb (11,564 eV) under ambient conditions. Energy calibration was performed using a standard metal foil.

To investigate electrical conductivity of nanowires, the TO NW and ATO NW were dispersed individually in isopropyl alcohol by sonication and then dropped on a silicon wafer with a SiO_2 thickness of 100 nm. The silicon wafer is made from a highly doped p-type silicon, which can be used as a back gate electrode. Additionally, metal electrodes consisting of Ti (30 nm)/Au (50 nm) were deposited by an electron beam evaporator and

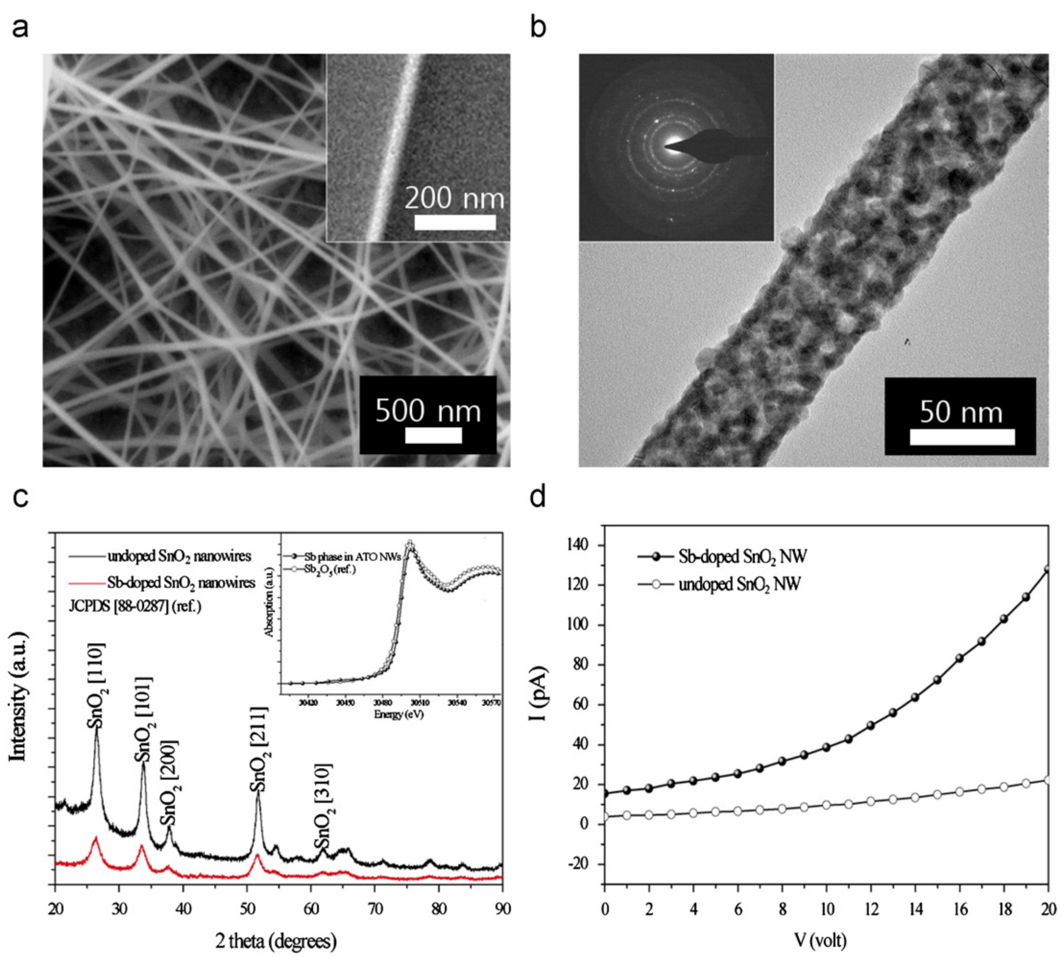

Fig. 2. (a) SEM and (b) HRTEM images (inset is selected area diffraction pattern) of ATO NWs. (c) XRD patterns of undoped SnO_2 and Sb-doped SnO_2 NWs; inset is XANES patterns of antimony in ATO NWs and Sb_2O_5. (d) *I–V* curves of single undoped SnO_2 nanowire and Sb-doped SnO_2 nanowire.