Current Applied Physics 16 (2016) 726–730

Contents lists available at ScienceDirect

Current Applied Physics

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

High efficiency AZO-InP nanopillar-based heterojunction solar cells

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
2 April 2016
Accepted 4 April 2016
Available online 8 April 2016

Keywords:
AZO
InP
Solar cells
Heterojunction
Nanostructure

ABSTRACT

This paper reports heterojunction solar cells consisting of InP nanopillars and aluminum-doped zinc oxide (AZO). The AZO layer sputtered on an InP surface is used not only as a transparent electrode, but also as an excellent rectifying junction with InP. More importantly, the wide-bandgap-AZO functions as a window layer of solar cells, thereby suppressing carrier recombination loss at the AZO-InP hetero-interface. The InP nanopillar array reduces the light reflectance and increases the optical path length of the solar cells. The AZO-InP nanopillar-based heterojunction solar cells exhibited an open-circuit voltage, short-circuit current density, fill-factor, and power-conversion efficiency of 0.68 V, 36.8 mA/cm^2, 68%, and 17.1%, respectively, under air-mass 1.5 simulated solar illumination (100 mW/cm^2).

1. Introduction

Semiconductor nanostructures have attracted considerable attention in optoelectronic applications because of their versatile and unique properties. For example, solar cells employing semiconductor nanopillars show significant enhancement of light absorption and carrier collection efficiency [1–3]. Semiconductor nanostructures, however, can result in severe carrier recombination loss because of their very high surface-to-volume ratio [4]. Indium phosphide (InP) is an ideal material to be employed as nanostructured solar cells because of its superior radiation resistance and longer minority carrier life time compared to those of Si and GaAs [5]. Recently, high-efficiency heterojunction solar cells consisting of InP nanowires and indium tin oxide (ITO) layer were demonstrated [6]. A transparent electrode is essential in nanostructured solar cells to collect light-generated carriers efficiently from their very large surface area. ITO, however, suffers from easy oxidation in air and the difficult control of tin diffusion into InP [7]. Aluminum-doped zinc oxide (AZO) is comparable to ITO because of its low electrical resistivity (~10^{-4} Ω-cm), the low absorption rate of visible rays, easy chemical etchability, and low material cost [8–11]. This paper reports high-efficiency AZO-InP nanopillar-based heterojunction solar cells. An *ex-situ* sputtered AZO layer was functioned as an excellent n-type junction on p-type InP. Importantly, a large-bandgap AZO layer reduces the surface recombination of InP dramatically. Thus, 17% power-conversion efficiency can be achieved from the heterojunction InP nanopillar array solar cells.

2. Experimental details

Fig. 1 presents the process sequence of the AZO-InP heterojunction solar cells. Initially, a 1-μm-thick layer of p-type InP ($p = 1 \times 10^{17}$ cm^{-3}) was grown on a heavily *p*-doped InP ($p = 2 \times 10^{18}$ cm^{-3}) substrate (AXT Inc.) using a metalorganic chemical vapor deposition (MOCVD, AIXTRON Inc.) system. Polystyrene (PS) beads (Molecular Probes, Inc.) were spin-coated on the InP sample to form a dot-array pattern (Fig. 1a and b) [12]. The diameter of the PS beads was then reduced by O_2 plasma etching (Fig. 1c). Subsequently, the patterned InP sample was etched by reactive ion etching with HBr:CH_4 plasma (24sccm:2sccm) at a pressure of 3mTorr, RF1 power of 150 W and RF2 power of 670 W. Subsequently, the PS beads were removed using a chloroform solution with sonication for 30 min. The InP sample was immersed in

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http://dx.doi.org/10.1016/j.cap.2016.04.004
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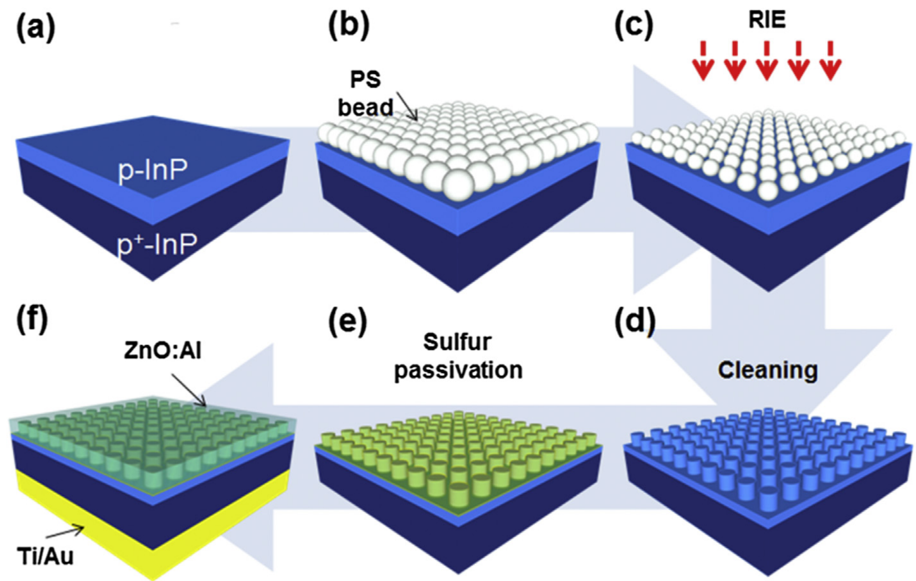

Fig. 1. Illustration of the fabrication sequence for the AZO-InP nanopillar array heterojunction solar cells: (a) a *p*-InP layer was grown on the p^+-InP substrate, (b) a PS beads monolayer was formed on the InP sample, (c) the diameter of PS beads was reduced after O_2 plasma etching, (d) the PS beads were removed in wet chemical solution, (e) the InP surface was passivated by sulfur, (f) the AZO film was sputtered on the InP surface and metal electrodes were deposited.

a $(NH_4)S$ solution for 150 s to passivate the InP surface. Shortly afterward, a 700-nm-thick AZO layer was deposited by RF-sputtering with ZnO and Al_2O_3 (2 wt %) targets. The chamber pressure at the base and deposition was 1×10^{-4} Pa and 0.073 Pa, respectively. The RF power was 500 W and the deposition rate was 33.3 nm/min. Finally, metal electrodes (Ti/Au = 20 nm/200 nm) were deposited on the top and bottom of the sample using an electron (e)-beam evaporator. The structural properties were examined by scanning electron microscopy (SEM, S-4800, Hitachi Inc.). The light reflectance was examined using a UV-VIS-NIR spectrometer equipped with an integrated sphere (Cary 500 Scan, Varian Inc.). A commercial solar simulator (Sol3A, Oriel Inc.) with a current (I) – voltage (V) measurement system (2400, Keithley Inc.) was used to characterize the solar cells. The external quantum efficiency was measured using a commercial PV measurement system (QEX7 IPCE, PV Measurement Inc.).

3. Results and discussion

Fig. 2 shows the characteristics of the planar AZO-InP heterojunction solar cells measured under air-mass 1.5 simulated solar illumination (100 mW/cm^2). For the heterojunction solar cells, the AZO layer thickness was optimized to be 700 nm. A reduction of the AZO layer thickness increases a sheet resistivity of the AZO layer while an increase of the AZO layer thickness decreases light absorption in InP layer, leading to a reduction of the heterojunction solar cells efficiency. For the passivated solar cells, the InP surface was immersed in a $(NH_4)S$ solution before sputtering the AZO layer while the unpassivated one was cleaned in BOE to remove the native oxide from the surface. The unpassivated solar cells show the open circuit voltage (V_{oc}) of 0.31 V, short circuit current density (J_{sc}) of 31 mA/cm^{-2}, fill factor (FF) of 68%, and efficiency (η) of 6.6%. These values suggest that the ex-situ sputtered AZO provides a good photovoltaic junction with p-type InP. The overall characteristics of the solar cells increase with the passivation process, as shown in Fig. 2. The passivated solar cell showed a V_{oc} of 0.35 V, J_{sc} of 32.9 mA/cm^{-2}, FF of 70%, and η of 8.1%. To improve the accuracy of the experiment, five solar cells are fabricated with and without a passivation process, as shown in Table 1. Overall, the solar cells

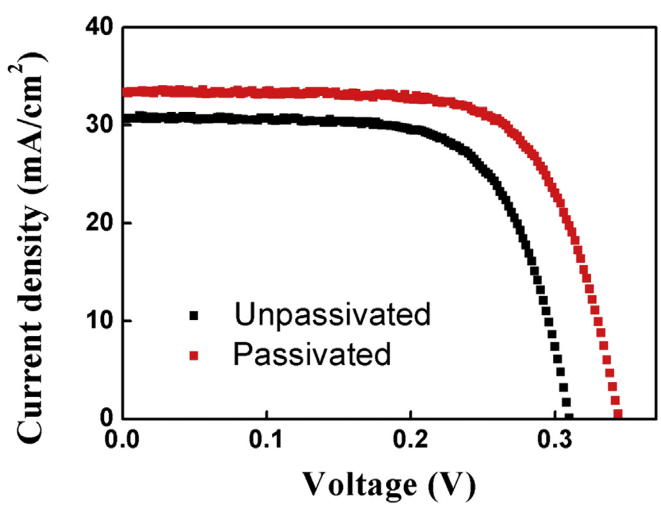

Fig. 2. Illuminated J-V characteristics of the AZO/InP solar cells with and without the sulfur passivation process.

Table 1
Characteristics of the planar AZO-InP heterojunction solar cells fabricated with and without a passivation process.

	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
Unpassivated solar cell	0.31	31.1	68	6.6
	0.31	31.0	68	6.5
	0.31	29.6	68	6.2
	0.32	31.3	65	6.5
	0.32	32.5	64	6.6
Passivated solar cells	0.35	32.9	70	8.1
	0.35	32.1	69	7.8
	0.35	33.3	69	8.1
	0.34	33.0	70	7.8
	0.34	33.6	68	7.8

fabricated with the passivation process showed an approximately 20% increase in efficiency. In III-V semiconductors, the existence of