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Hybrid tandem photovoltaic devices with a transparent conductive interconnecting recombination layer

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ABSTRACT

We demonstrate hybrid tandem photovoltaic devices with a transparent conductive interconnecting recombination layer. The series-connected hybrid tandem photovoltaic devices were developed by combining hydrogenated amorphous silicon (a-Si:H) and polymer-based organic photovoltaics (OPVs). In order to enhance the interfacial connection between the subcells, we employed highly transparent and conductive indium tin oxide (ITO) thin layer. By using the ITO interconnecting layer, the power conversion efficiency of the hybrid tandem solar cell was enhanced from 1.0% (V_{OC} = 1.041 V, J_{SC} = 2.97 mA/cm^2, FF = 32.3%) to 2.6% (V_{OC} = 1.336 V, J_{SC} = 4.65 mA/cm^2, FF = 41.98%) due to the eliminated interfacial series resistance.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) solar cells have extensively studied due to their potential for low-cost and large-area solar cells [1,2]. However, their power conversion efficiency (PCE) has been stagnant during the last decade mainly due to their narrow absorption spectrum which limits the utilization of the full solar spectrum [3]. A possible solution to enhance the PCE of solar cells is to stack multiple photoactive materials with different bandgaps. Previously, shah and co-workers developed the 'micromorph' tandem solar cell with a-Si:H as a front cell and microcrystalline Si (mc-Si:H) as a back cell [4]. Although the micromorph tandem cells showed enhanced PCE, the even thicker absorber layer of mc-Si:H layers should be formed to generate sufficient photocurrent due to the low absorption coefficient.

Recently, solution-processable bulk-heterojunction OPV has been attracted much attention as the promising future photovoltaic technologies [5,6]. Our group demonstrated the 'organic–inorganic hybrid' tandem solar cells by combining the a-Si:H and organic photovoltaic cells (OPVs) with a low bandgap semiconducting polymer which can extend the spectral response [7]. The tandem solar cells suffer from the inefficient interfacial contact between the front and back subcells [7–9]. Although we improved the interfacial contact between the subcells by using evaporated MoO_3 as an efficient hole transporting layer, interfacial series resistance $R_{s,int}$ which is additionally generated from the interface could not be completely eliminated. To eliminate the $R_{s,int}$ between the subcells, the efficient interconnecting layer should be developed. For the efficient interconnecting layer, the following requirements should be qualified. The interconnecting layer should be (1) electrically conductive to minimize the resistance loss and (2) optically transparent to maximize the absorption at the photoactive layers. Previously, valuable efforts to develop the transparent and conductive electrodes were provided [10,11].

In this work, we demonstrate that the PCE of the hybrid tandem solar cell was enhanced from 1.0% to 2.6% by employing indium tin oxide (ITO) thin interlayer (ITL) as the efficient interconnecting layer. The ITO interconnecting layer showed high transparency and electrical conductivity. The enhanced PCE of the hybrid tandem solar cell is attributed to the eliminated $R_{s,int}$ between the subcells which was analyzed with dark current characteristics.

2. Material and methods

The hybrid tandem photovoltaic devices were fabricated on indium tin oxide (ITO) coated glass substrates with a sheet resistance of 10 Ω/square. The a-Si:H layers were deposited on the ITO substrate with a very-high-frequency plasma-enhanced chemical vapor deposition (VHF-PECVD) using SiH_4, Ar, H_2, and doping gases. For *p*-type and *n*-type doping, B_2H_6 and PH_3 gases were used, respectively. Thicknesses of the a-Si:H layers were about 5 nm, 120 nm, and 25 nm for *p*-, *i*-, and *n*-layers, respectively. The 10-nm-thick ITO interconnecting layer was

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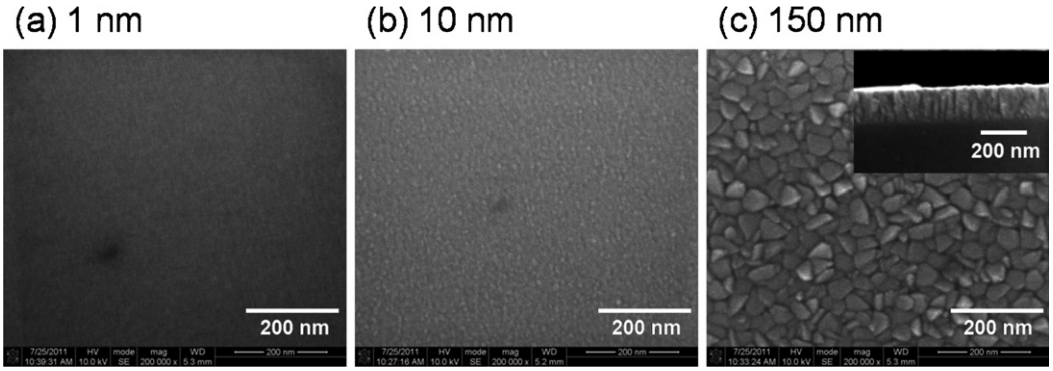

Fig. 1. SEM images of ITO layers deposited on Si wafers by DC magnetron sputtering at a substrate temperature of 230 °C with the layer thickness of 1 nm (a), 10 nm (b), and 150 nm (c). Inset in (c) is a cross-sectional image.

deposited on the *n*-type a-Si:H layer by DC magnetron sputtering with an ITO target and the film growth rate was 0.1 nm/s. To prepare a hole transporting layer onto the ITO interconnecting layer, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS, VP AI 4083 from H.C. Stark) was applied. The 30-nm-thick PEDOT:PSS layer was spin-casted at 4000 rpm for 40 s and dried at 110 °C for 10 min. We employed poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b′]-dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)] (PCPDTBT) [12,13] as a low bandgap donor material and [6,6]-phenyl-C_{71} butyric acid methyl ester ($PC_{70}BM$) as an electron acceptor in the active layer of the OPV cell. The 70-nm-thick active layer comprised of PCPDTBT (Lumtec) and $PC_{70}BM$ (nano-C) was spin-coated from a chlorobenzene solution with a weight ratio of 1:3.5 and a polymer concentration of 6 mg/ml at 2000 rpm for 25 s on top of the PEDOT:PSS layer. The 20-nm-thick nanocrystalline TiO_2 layer was spin-casted from 0.4 wt% of ethanol solution at 4000 rpm for 30 s according to the published method [14,15]. The active area of 0.4 cm^2 was defined by overlapping the Al top electrode with the underlying ITO pattern. For the comparison, single-junction solar cells were also fabricated with the device configuration of ITO/a-Si:H(*p*-*i*-*n*)/Al for the a-Si:H single-junction cell and ITO/PEDOT:PSS/PCPDTBT:$PC_{70}BM$/TiO_2/Al for the OPV single-junction cell. For scanning electron microscopy (Nova-SEM, FEI) observation, the ITO thin layers were deposited on Si wafers. For the transmittance measurement (Perkin Elmer, Lambda 35 UV/VIS Spectrometer), the ITO thin layers were deposited on slide glasses. The electrical conductivity was measured with 4-pin probe system (Mitsubishi Chemical Analytech, MCP-T610). The current density–voltage (*J*–*V*) characteristics were measured by a Keithley 2400 source meter with a 150 W solar simulator (Newport). External quantum efficiency (EQE) was measured using incident photo-to-current efficiency measurement system (PV Measurements, Inc.).

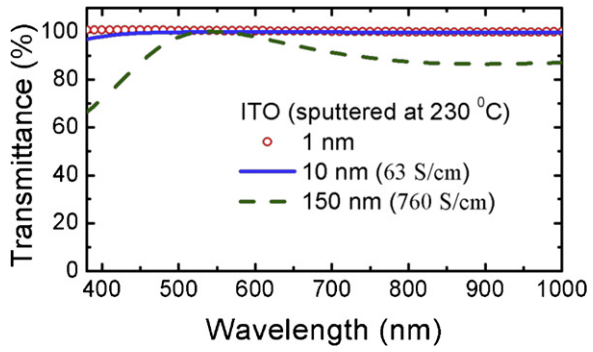

Fig. 2. UV–Vis transmittance of the ITO layers with variable layer thicknesses. Electrical conductivity of 10 nm and 150 nm-thick ITO layers were 63 S/cm and 760 S/cm, respectively.

3. Results and discussion

Fig. 1 shows the scanning electron microscopy (SEM) images of ITO layers deposited on Si wafer by DC magnetron sputtering at a substrate temperature of 230 °C with the layer thickness of 1 nm, 10 nm, and 150 nm. In Fig. 1a and b, the thin ITO layer showed discontinuous surface morphologies, whereas Fig. 1c shows the crystalline ITO domains of the thick (150 nm) ITO layer clearly.

Although the discontinuous morphology results relatively low electrical conductivity, the discontinuous morphology is conducive to the optical transmittance as can be seen in Fig. 2. The thin ITO layer was highly transparent so that the light absorption of the back cell can be maximized in the tandem device architecture.

Fig. 3 shows the current density–voltage (*J*–*V*) characteristics of the single-junction and tandem devices. The corresponding

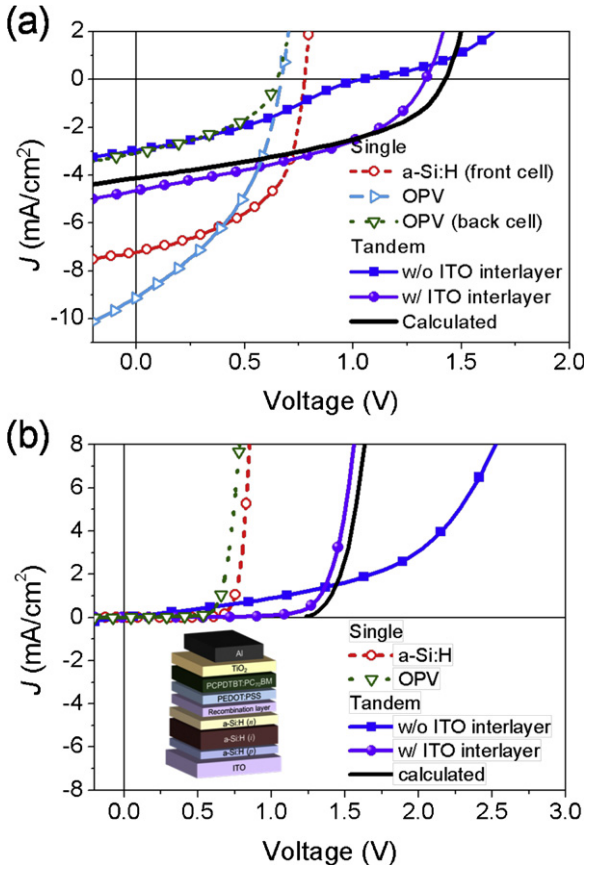

Fig. 3. *J*–*V* characteristics measured under illumination of 100 mW/cm^2 (a) and in the dark (b). Inset in (b) is a schematic diagram showing the device configuration of the hybrid tandem solar cell.