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Improvement in ultra-thin hydrogenated amorphous silicon solar cells with nanocrystalline silicon oxide

Jia Fang[a,b,c,d], Baojie Yan[a,b,*], Tiantain Li[a,b], Changchun Wei[a,b], Qian Huang[a,b], Xinliang Chen[a,b], Guangcai Wang[a,b], Guofu Hou[a,b], Ying Zhao[a,b,c,d], Xiaodan Zhang[a,b,c,d,*]

[a] Institute of Photoelectronic Thin Film Devices and Technology, Nankai University, Tianjin 300071, PR China
[b] Key Laboratory of Photoelectronic Thin Film Devices and Technology of Tianjin, Tianjin 300071, PR China
[c] Key Laboratory of Optical Information Science and Technology of Ministry of Education, Tianjin 300071, PR China
[d] Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin 300072, PR China

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ABSTRACT

Ultra-thin a-Si:H *p-i-n* solar cell has been proposed as advance to form three-dimensional structures on nano-structured substrates for achieving optically thick and electrically thin solar cells. However, over the years, although extensive studies have been carried out, no high efficiency was achieved yet. We found that not only the short circuit current density (J_{sc}) decreases, but also the open circuit voltage (V_{oc}) and fill factor (FF) decreases with the reduction of *i*-layer thickness, which is opposite to the expectation. We investigated the possible root-causes for this unusual phenomenon and speculated the direct recombination of the electrons in the *n*-layer and the holes in the *p*-layer by tunneling through the thin *i*-layer is the main reason for the reduced V_{oc} and FF in ultra-thin solar cells. Furthermore, the absorption in the doped layers is the most critical limitation for ultra-thin silicon solar cell efficiency because the doped layer thickness becomes comparable to the intrinsic layer. To resolve this issue, we used nanocrystalline silicon oxide (nc-SiO_x:H) doped layers with a wide bandgap to reduce the parasitic absorption in the doped layers and the highly asymmetric conductivity improves the carrier collection and made a significant improvement in the cell efficiency. We achieved 8.79%, 7.65%, and 5.32% efficiencies with the *i*-layer thickness of only 70 nm, 50 nm and 20 nm, respectively, which are the highest ones in ultra-thin silicon solar cells.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) has been an attractive material for photovoltaic (PV) solar energy application. Because of the thin film nature and the capability on large area foreign substrates, a-Si:H solar cell has been considered as one of the low cost photovoltaic technologies. It has attracted extensive continue studies and gone on a long and rough road from the initial laboratory study [1], industrial research and development [2–4], to large volume PV module and laminate production [5,6]. However, in recent years, with the significant cost reduction and efficiency improvement of crystal silicon (c-Si) PV modules, a-Si:H PV industry has been shrunk significantly because of the lower efficiency and poorer stability than the c-Si counterparts. The low efficiency is mainly due to the poor carrier transport with low carrier mobility-lifetime product ($\mu\tau$) [7,8], especially for holes. The low $\mu\tau$ product limits the absorber *i*-layer thickness in the *p-i-n* structured solar cell, where the *p, i, n* represent the *p*-layer, *i*-layer and *n*-layer, respectively. It has been shown that the solar cell efficiency increases with the *i*-layer thickness and then saturates at around 300 nm [9]. However, the stable cell efficiency reaches the maximum at a much thinner *i*-layer than the initial efficiency, and then decreases with the *i*-layer thickness because the light-induced defect generation leads to a high recombination rate. In addition, a portion of the *i*-layer becomes electric field free in the light soaked state caused by the trapped charges if the *i*-layer is too thick. Therefore, the optimization of a-Si:H solar cell efficiency has been faced a contradicted case. Optically one needs to increase the *i*-layer thickness for enough light absorption to generate a high photocurrent density, but electrically to keep the *i*-layer thin enough for a high built-in electric field to collect the photo-generated carriers and to avoid serious light-induced efficiency degradation.

To resolve the optical and electrical contradiction, three dimensional (3D) solar cell structures have been proposed by using various 3D nano- or micro-structures, such as nano-wire [10–12], nano-dome [13,14], nano-cone [15,16], nano-pillar [17,18] and other nanostructures [19–26]. Two major promises have been proposed. First, the

* Corresponding authors at: Institute of Photoelectronic Thin Film Devices and Technology, Nankai University, Tianjin 300071, PR China.
E-mail addresses: Baojie.yan@yahoo.com (B. Yan), xdzhang@nankai.edu.cn (X. Zhang).

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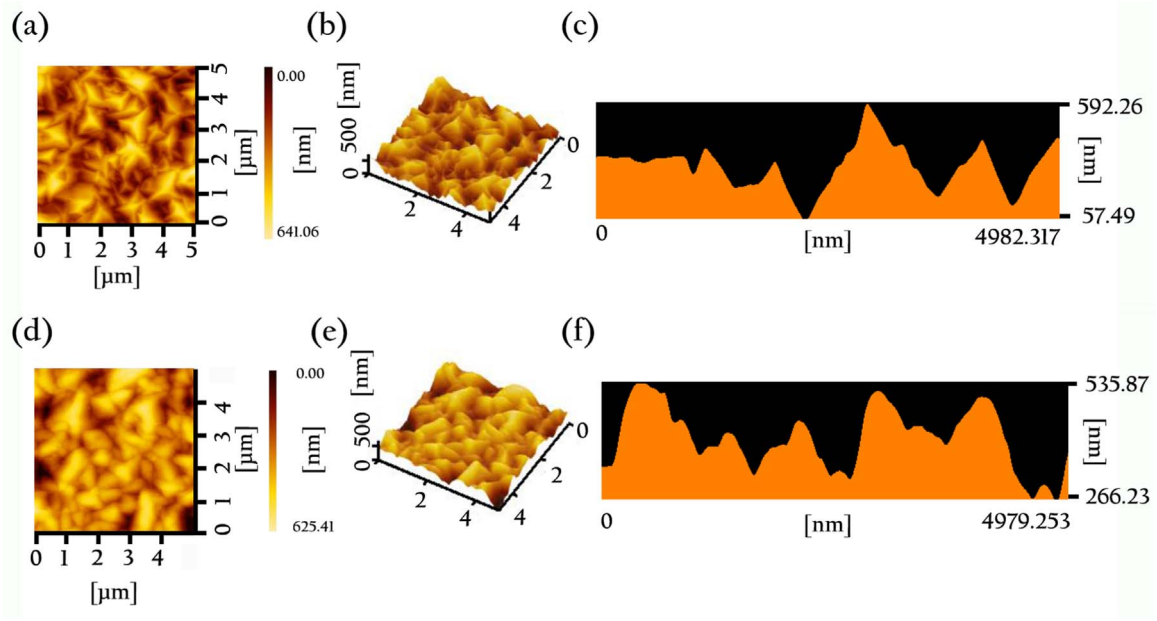

Fig. 1. AFM images of a BZO substrate and an ultra-thin a-Si:H solar cell. (a) top view, (b) 3D image, and (c) cross section view of the BZO substrate; (d) top view, (e) 3D image, and (f) cross section view of the ultra-thin solar cell with 70-nm thick *i*-layer.

3D solar cells can use a very thin absorber layer because the vertical dimension provides enough volume for light absorption just like a thick *i*-layer, and the thin *i*-layer results in a high built-in electric field for efficient carrier collection because the carriers transport perpendicularly to the vertical surface on the wall of the 3D structures. Therefore, the 3D structured solar cells has been ideally considered as optically thick and electrically thin, and believed to have a higher efficiency and a better stability than the conventional planar 2D solar cells. Second, the 3D solar cells were believed to have much better light trapping than 2D solar cells because of the equivalence of highly textured structures with wave-guide modes for effective light coupling and trapping. However, over several years of extensive study on the ultra-thin 3D a-Si:H solar cells, no higher efficiency than the conventional planar solar cells [27,28] has been attained by using 3D structured a-Si:H solar cells. There could be some technical difficulties in the 3D solar cell design, fabrication, and optimization, and could also have some fundamental limitations for the *i*-layer thickness in ultra-thin a-Si:H solar cells.

First, the conventional plasma enhanced chemical vapor deposition (PECVD) is difficult to make a conformal deposition on 3D structures with a high aspect ratio, where the deposited film is thinner in the bottom part than on the top part of 3D structures. Second, microstructural defects such as micro-voids easily form in the sharp valleys on the substrates and cause micro-shunts [29]. Third, the material quality might be lower in the materials deposited on a highly textured substrate than on a flat substrate because of the reduced lateral diffusion length of growth spices during the deposition. Fourth, it is well known that doped a-Si:H films have a much high defect density and cannot be used as the absorber layer in a *p-n* junction solar cell as those in c-Si cells. One has to use an *i*-layer sandwiched between the *p* and *n* layers to form a *p-i-n* structure to have a good solar cell performance, where the *i*-layer absorbs the sun light to generate electron-hole pairs and the difference of the Fermi levels in the *p*-layer and *n*-layer generates an electric field to collect the photo carriers to form photocurrent. Obviously, the *i*-layer cannot be too thin to separate the *p* and *n* layer for forming an effective built-in potential and to absorb most of the light for generating high photocurrent. Except for the issues mentioned above, there are could be some other fundamental limitations for the *i*-layer thickness of a-Si:H *p-i-n* solar cells.

The objective of this work is to optimize ultra-thin a-Si:H solar cells and explore the possible mechanisms of limiting the ultra-thin a-Si:H solar cell efficiency. We chose a simple approach by making ultra-thin a-Si:H on our optimized boron doped zin-oxide (BZO) coated glass substrate [30,31]. Although the BZO has some textures, but the roughness on the BZO is much lower than those 3D structured substrates. Logically, if one cannot make reasonable good ultra-thin solar cells on the 2D substrate, especially high open circuit voltage (V_{oc}) and fill factor (FF), it is hardly to expect to make high efficiency ultra-thin solar cells on 3D structured substrates because of the additional issues associated with the 3D substrates.

2. Experimental details

The optimized BZO layers were deposited using a low pressure chemical vapor deposition (LPCVD) method on cleaned glasses at 150 °C as the substrates for solar cell fabrications. a-Si:H *p-i-n* structured ultra-thin solar cells with the *i*-layer thickness of 20–70 nm were deposited using a multi-chamber PECVD system at the substrate temperature of 210 °C. The *p*-layer was a wide bandgap B-doped nanocrystalline silicon oxide (*p*-nc-SiO_x:H) for reducing the absorption in the *p*-layer, which is extremely important for ultra-thin solar cells. Two kinds of *n*-layers were used, conventional P-doped a-Si:H (*n*-a-Si:H) and wide bandgap P-doped nanocrystalline silicon oxide (*n*-nc-SiO_x:H) for studying the absorption in the *n*-layer. The details and optimizations of the cell performance are available elsewhere [32,33].

The surface structures of the BZO were measured using an atomic force microscopy (AFM) (SPA 400 AFM) with the surface roughness characterized by the root-mean-square (RMS). The conformity of the ultra-thin a-Si:H solar cells on the BZO substrates were measured by using a cross sectional transmission electron microscopy (TEM) (FEI Novanano lab 200).

The solar cell performance was characterized by the current density versus voltage (J-V) measurement under an AM1.5 solar simulator (WXS-156S-L2, AM1.45GMM by Wacom Co.) with 100 mW/cm^2 of light intensity at 25 °C, and by the external quantum efficiency (EQE) measured with an EQE system (PV measurement QEX10).

3. Results and discussion

Fig. 1 shows the AFM images of the BZO substrate (a-c) used in this study and an ultra-thin a-Si:H solar cells (d-f) with a 70-nm thick *i*-layer, where (a) is the planar view, (b) the 3D image, and (c) the cross