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High-efficiency micromorph solar cell with light management in tunnel recombination junction

Jia Fang [a,b], Lisha Bai [a,b], Tiantian Li [a,b], Guofu Hou [a], BaoZhang Li [a], Changchun Wei [a], Guangcai Wang [a], Dekun Zhang [a], Ying Zhao [a,b], Xiaodan Zhang [a,b,*]

[a] Institute of Photo-Electronic Thin Film Devices and Technology of Nankai University, Key Laboratory of Photo-electronic Thin Film Devices and Technology, Tianjin 300071, PR China
[b] Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin 300072, PR China

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ABSTRACT

Effective tunnel recombination junctions (TRJs) are crucial to achieve high conversion efficiencies in hydrogenated amorphous/ microcrystalline silicon (a-Si:H/μc-Si:H) micromorph solar cells. In conventional TRJs, the n-μc-Si:H layer is used to form an ohmic contact between the n- and p-type layers, which introduces additional absorption loss in the TRJs. Here we demonstrated an effective TRJ without using the n-μc-Si:H layer in a-Si:H/μc-Si:H micromorph solar cells, which we denote as an evolutionary TRJ. In comparison to the conventional n-μc-SiO_x:H/n-μc-Si:H/p-nc-SiO_x:H TRJs, the evolutionary structure reduces the parasitic absorption and thus significantly increases the short-circuit current density (J_{SC}) of the bottom cell. A high initial efficiency of 13.65% has been achieved for the a-Si:H/μc-Si:H micromorph solar cells deposited on the as-grown metal organic chemical vapor deposited ZnO:B substrates.

1. Introduction

Due to its nontoxicity, abundance of raw materials, and low-cost manufacturing, thin-film silicon-based photovoltaic technology based on hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H) as absorbers has attracted much attention from both research and industrial communities.

To enhance the recombination of electrons exiting in the n-layer of the top cell and the holes exiting in the p-layer of the bottom cell in micromorph solar cells under illumination and to avoid the deterioration of the cell performance caused by carrier accumulation, a layer with high conductivity, such as a n- or p-μc-Si:H layer, is inserted between the n-layer of the top cell and the p-layer of the bottom cell to form a tunnel recombination junction (TRJ) [1,2].

In addition, the use of a n-μc-SiO_x:H layer with a low refractive index and low absorption has been proposed in the micromorph cells in which the n-μc-SiO_x:H layer simultaneously functions as the n-layer of the top cell and the intermediate reflector layer (IRL). These roles of the dual-functional n-μc-SiO_x:H films have been reported by several groups [3-7]. Increasing the thickness or decreasing the refractive index of the n-μc-SiO_x:H IRL results in a shift of the current from the bottom cell to the top cell [8,9]. Meanwhile, n-μc-SiO_x:H is a mixed phase material with an oxygen rich amorphous silicon oxide phase, which improves the band gap of the film and a doped microcrystalline silicon phase, which enhances the conductivity of the material [10,11]. Thus, the application of n-μc-SiO_x:H layers in thin-film silicon solar cells could improve the performance of devices even on highly textured substrates [4,5].

In the case of conventional TRJs (n-μc-SiO_x:H/n-μc-Si:H/p-nc-SiO_x:H) in a-Si:H/μc-Si:H micromorph solar cells (as shown in Fig. 1 (left)), the n-μc-SiO_x:H layer with a lower refractive index acts as the n-layer of the top cell and the IRL, while the thin n-μc-Si:H layer inserted between the sub-cells to form the TRJ improves recombination of carriers originating from each cell. However, a current gain in the top cell attributed the IRL inevitably leads to an automatic decline in the short-circuit current density (J_{SC}) of the bottom cell [8,9]. Therefore, the bottom cell becomes the current limiting cell in the device. Moreover, the high conductivity and low band gap of the inserted n-μc-Si:H layer leads to optical absorption losses and further lowers the J_{SC} of the bottom cell.

To overcome this limitation, we proposed an evolutionary TRJ in micromorph solar cells. Meanwhile, we found other groups also applied this evolutionary TRJ (suitable thick n-μc-SiO_x:H/p-nc-SiO_x:H) in micromorph solar cells [8,12]. However, they didn't provide any detail information of the evolutionary TRJ. In this

* Corresponding author at: Institute of Photo-Electronic Thin Film Devices and Technology of Nankai University, Key Laboratory of Photo-electronic Thin Film Devices and Technology, Tianjin 300071, PR China.
E-mail address: xdzhang@nankai.edu.cn (X. Zhang).

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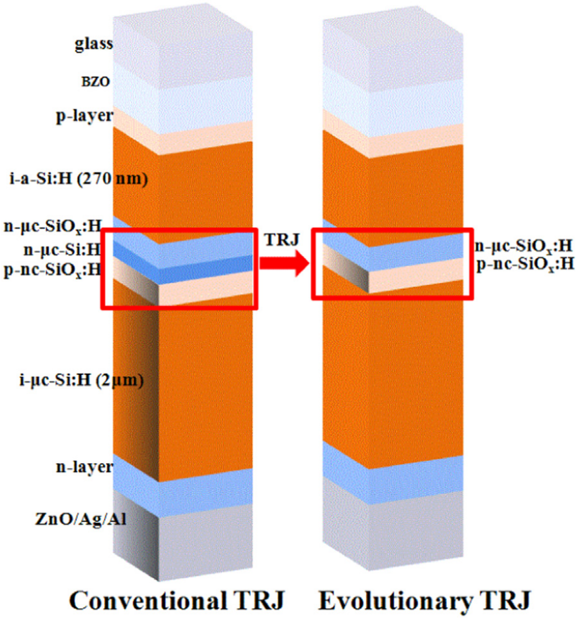

Fig. 1. Schematic structure of a-Si:H/μc-Si:H micromorph solar cells with the conventional and evolutionary TRJs.

paper, we comparatively study the conventional and evolutionary TRJ and apply them in micromorph solar cells. The structure of cells is shown in Fig. 1. The optical, structural, and electrical contact properties of the different TRJs were studied in details. The application of the evolutionary TRJ in a-Si:H/μc-Si:H micromorph solar cells led to high initial conversion efficiencies. In these evolutionary TRJs, the n-μc-SiO_x:H functioned as the n-layer of the top cell, IRL, and the n/p TRJ in combination with the following deposited p-nc-SiO_x:H film.

2. Materials and methods

2.1. Fabrication of silicon oxide films

The doped SiO_x:H thin films were deposited at 210 °C using a radio frequency-plasma enhanced chemical vapor deposition (RF-PECVD) cluster system with a mixture of H_2, SiH_4 and CO_2 as the precursor gases. The n-type and p-type doping were obtained by adding phosphine (pH_3) and trimethylboron (TMB) to the precursor mixture, respectively. The deposition pressures were 1.3 and 1.98 Torr for n-type and p-type films, respectively. The lateral conductivity of the TRJ was obtained by evaporating Al electrodes on the p-nc-SiO_x:H top layer surface. Raman spectroscopy was carried out using a Renishaw inVia Raman microscope with an excitation wavelength of 325 nm.

2.2. Fabrication of a-Si:H/μc-Si:H tandem solar cells

The p-i-n type a-Si:H/μc-Si:H micromorph solar cells as structured in Fig. 1 were deposited at 210 °C by RF-PECVD for the a-Si:H absorber and doped layers and by very high frequency-PECVD for the μc-Si:H absorber layers. The thicknesses of the intrinsic layers were 270 nm and 2 μm for the top and bottom subcells, respectively. The textured boron-doped zinc oxide (ZnO:B) with a root mean square roughness (RMS) of ~90 nm prepared by metal organic chemical vapor deposition (MOCVD) was used as the front electrode. The current-voltage (*J-V*) characteristics of solar cells (active area of 0.25 cm^2) were measured under the standard conditions (AM 1.5 G, 100 mW/cm^2) at 25 °C using a dual-lamp

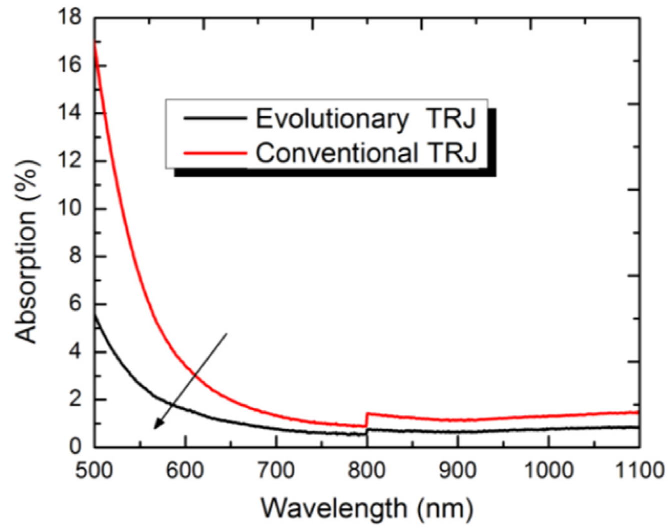

Fig. 2. Optical absorption of the conventional and evolutionary TRJs.

solar simulator (WXS-156 S-L2, AM 1.5 GMM). The external quantum efficiency (*EQE*) measurements (QEX10, PV Measurement) were obtained by using the proper bias illumination. The short-circuit current density (*Jsc*) values were calculated from the *EQE* measurements by weighting with the AM 1.5G spectrum.

3. Results and discussion

3.1. Structural characterization

The structures of the micromorph cells with conventional and evolutionary TRJs are shown in Fig. 1. The conventional TRJs consist of layer stack n-μc-SiO_x:H/n-μc-Si:H/p-nc-SiO_x:H, while evolutionary TRJs (n-μc-SiO_x:H/ p-nc-SiO_x:H) eliminate the use of more absorptive n-μc-Si:H layer between the two doped silicon oxide layers. Firstly, the absorption of the two types of TRJs was deduced from the optical reflection and transmission spectra. The thicknesses of the n-μc-Si:H, n-μc-SiO_x:H and p-uc-SiO_x:H layers were about 10, 70 and 15 nm, respectively. As shown in Fig. 2, the elimination of the n-μc-Si:H layer in an evolutionary TRJ led to a significant decrease in parasitic absorption loss for wavelengths shorter than 800 nm.

In micromorph solar cells with the evolutionary TRJs, the n-μc-SiO_x:H layer is required to form an ohmic contact with the p-nc-SiO_x:H layer of the bottom cell. The series resistances (R_s) of the evolutionary and conventional TRJs were measured to assess the quality of the TRJs. The R_s was obtained through *J-V* measurements with a device structure shown in the inset of Fig. 3a [13,14]. It is noticed that the three curves with the conventional TRJs are overlapped each other and show a good linear shape, indicating a good ohmic contact; while the three curves with the evolutionary TRJs show a strong dependence on the *n*-uc-SiO_x:H thickness. The sample with thinner *n*-uc-SiO_x:H layer not only has a high resistance, but also show a non-linear behavior, indicting a barrier needed to be overcome for carriers before recombining to form a continue current flow. The junction resistances were calculated using the data with low bias voltage, the results are shown in Fig. 3b, the conventional TRJs with a highly conductive n-μc-Si:H layer all have a low R_s ($<1\ \Omega\ cm^2$), which exhibits little dependence on the thickness of *n*-SiO_x:H layer. On the contrary, the R_s of the evolutionary TRJs shows a strong dependence on the thickness of the *n*-uc-SiO_x:H layer. A high R_s (5.8 $\Omega\ cm^2$) is observed for a relatively thin layer of *n*-uc-SiO_x:H (25 nm). As the