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Amorphous silicon/crystal silicon heterojunction double-junction tandem solar cell with open-circuit voltage above 1.5 V and high short-circuit current density

Jia Fang[a,b,c,d], Qianshang Ren[a,b,c,d], Fengyou Wang[a,b,c,d], Changchun Wei[a,b], Baojie Yan[a,b], Ying Zhao[a,b,c,d], Xiaodan Zhang[a,b,c,d,*]

[a] Institute of Photoelectronic Thin Film Devices and Technology of 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

Photovoltaic device requires light-absorbing materials that are highly efficient, low cost, lightweight, and stable during operation. Here we demonstrate the use of a hydrogenated amorphous silicon (a-Si:H) top cell and a crystal silicon heterojunction (HIT) bottom cell to form a double-junction solar cell with a high open circuit voltage (V_{OC}), which is potentially functioned in the solar-to-hydrogen generation process and the replacement of chemical battery. Our photovoltaic device shows a high overall V_{OC} of 1.561 V and a short current density of over 14 mA/cm^2, which outperforms all other reported pure silicon-based double-junction solar cells. The newly developed a-Si:H/HIT double-junction solar cells hold the promise for some potential applications.

1. Introduction

Silicon-based solar cells offer the attractive prospect for providing high-efficiency, low-cost and large-area photovoltaic modules due to the abundant raw materials on the earth. To date, the highest power conversion efficiency of the state-of-the-art single junction crystal silicon heterojunction solar cells (HIT) has reached 26.7% as a result of tremendous efforts in the combination of high quality N-type crystal silicon (c-Si) wafer, high quality intrinsic hydrogenated amorphous silicon (a-Si:H) thin film passivation, and interdigitated back contact (IBC) process [1,2]. Although a high short-circuit current density (J_{SC}) above 41 mA/cm^2 has achieved for the HIT-IBC device, the open circuit voltage (V_{OC}) around 740 mV of the single-junction cell limits its grand application. In order to increase V_{OC} for some special applications such as water-splitting hydrogen generation and replacement of chemical batteries, a minimal requirement for Voc is 1.5 V. For these applications, thin film silicon-based multi-junction solar cells have received considerable attentions in the past few years [3–7]. Generally, in the case of double-junction solar cells, a wide band-gap top cell and a narrow band-gap bottom cell are connected in series, in which the short wavelength photons of the incident light are absorbed in the top cell and the remaining long wavelength photons are absorbed in the bottom cell. Therefore, a multi-junction solar cell achieves a broad solar spectral coverage and reduces the thermalisation losses in the device. Meanwhile, due to the series inter-connection of the sub-cells, an ideal high V_{OC} can be obtained by summing the voltages of the component cells with a limited loss in the tunnel junction. For thin film silicon based double-junction solar cells, the best conversion efficiency of 14.8% with V_{OC} of 1.424 V and J_{SC} of 14 mA/cm^2 has been reported with an a-Si:H/microcrystalline silicon (μc-Si:H) tandem structure [8]. Such high efficiency is mainly attributed to the successful fabrication of multi-scale micro-features in the transparent front electrode, the optimized plasma enhanced chemical vapor deposition (PECVD) process for the silicon layers, and the optimized cell structures in the sub-cells. However, the thin film silicon-based double-junction solar cells simultaneous with high V_{OC} (> 1.5 V) and high J_{SC} still has not been reached yet.

In this contribution, a conversion efficiency of 14.26% is achieved using an a-Si:H/HIT double-junction solar cell structure with the combination of a wide band-gap a-Si:H top cell and a narrow band-gap HIT bottom cell. It is reported that a-Si:H solar cells have a tunable V_{OC} in the range from 0.88 up to 1.04 V [9–11], which is related to the relatively wide band-gap of intrinsic a-Si:H layer and optimized doped layers. Meanwhile, a-Si:H solar cells also possess a high *EQE* at the short wavelengths when the top contact and the p-layer are optimized. These properties make a-Si:H solar cell a good candidate for the top cell in

* Corresponding author at: Institute of Photoelectronic Thin Film Devices and Technology of Nankai University, Tianjin 300071, PR China.

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tandem solar cells. More importantly, a-Si:H solar cells use an abundant raw materials; thin film silicon solar cells with light weight, low temperature process with low cost has been well developed for many years [12]. As a result, the fabrication technology of thin film silicon based single-junction and multi-junction solar cells has been well-established, which is technically compatible with the following fabrication of HIT solar cells using a thin intrinsic a-Si:H (i-a-Si:H) layer for the c-Si surface passivation and doped a-Si:H alloy layers for carrier transport.

2. Experiment details

All silicon thin films were deposited at 210 °C using a radio frequency-plasma enhanced chemical vapor deposition (RF-PECVD) cluster system. The doped SiO_x:H thin films were prepared by a mixture of H_2, SiH_4 and CO_2as the precursor gases. The n-type and p-type doped layers were realized by adding phosphine (PH_3) and trimethylboron (TMB) to the precursor mixture, respectively. The deposition pressures were1.3 and 1.98 Torr for n-type and p-type films, respectively.

The n-i-p type single-junction a-Si:H solar cells and HIT solar cells were deposited on a smooth stainless steel substrate without back reflector and on as-cut monocrystalline Czochralski (Cz) silicon (100) wafers (2-inch diameter, n-type, 1–3 Ω cm, 300 ± 10 µm thickness) textured with our own developed etching process [13], which are shown in Fig. 1(a) and (b), respectively. The a-Si:H/HIT double-junction solar cells as structured in Fig. 2(a). The cross-sectional images of the a-Si:H/HIT solar cell were measured by a SUPRA 55VP scanning electronicmicroscope. The current-voltage (*J-V*) characteristics of solar cells (active area of 0.25 cm^2) were measured under the standard conditions (AM1.5G, 100 mW/cm^2) at 25 °C using a dual-lamp solar simulator (WXS-156S-L2, AM1.5GMM). The external quantum efficiency (*EQE*) measurements (QEX10, PV Measurement) were made 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

Fig. 1(a) illustrates the device architecture of the a-Si:H solar cell. The n-i-p type a-Si:H solar cells were deposited with a multi-chamber PECVD system on a smooth stainless steel substrate without back reflector. The doped nanocrystalline silicon oxide (nc-SiOx:H) p- and n-layer functioned as the doped layers to split the Fermi-levels and at the same time as the window layer and the back reflected layer, respectively. Fig. 1(b) shows the schematic structure of the HIT solar cell. The surface dangling bonds of the c-Si wafer are well passivated by introducing the high-quality i-a-Si:H layers between the doped layers and the c-Si wafer. The doped silicon oxide layer with the attractive advantages of low light absorption, tunable refractive index, high vertical conductivity and low lateral conductivity [14–17], has been proposed to act as doped layers in both the a-Si:H solar cells and HIT solar cells.

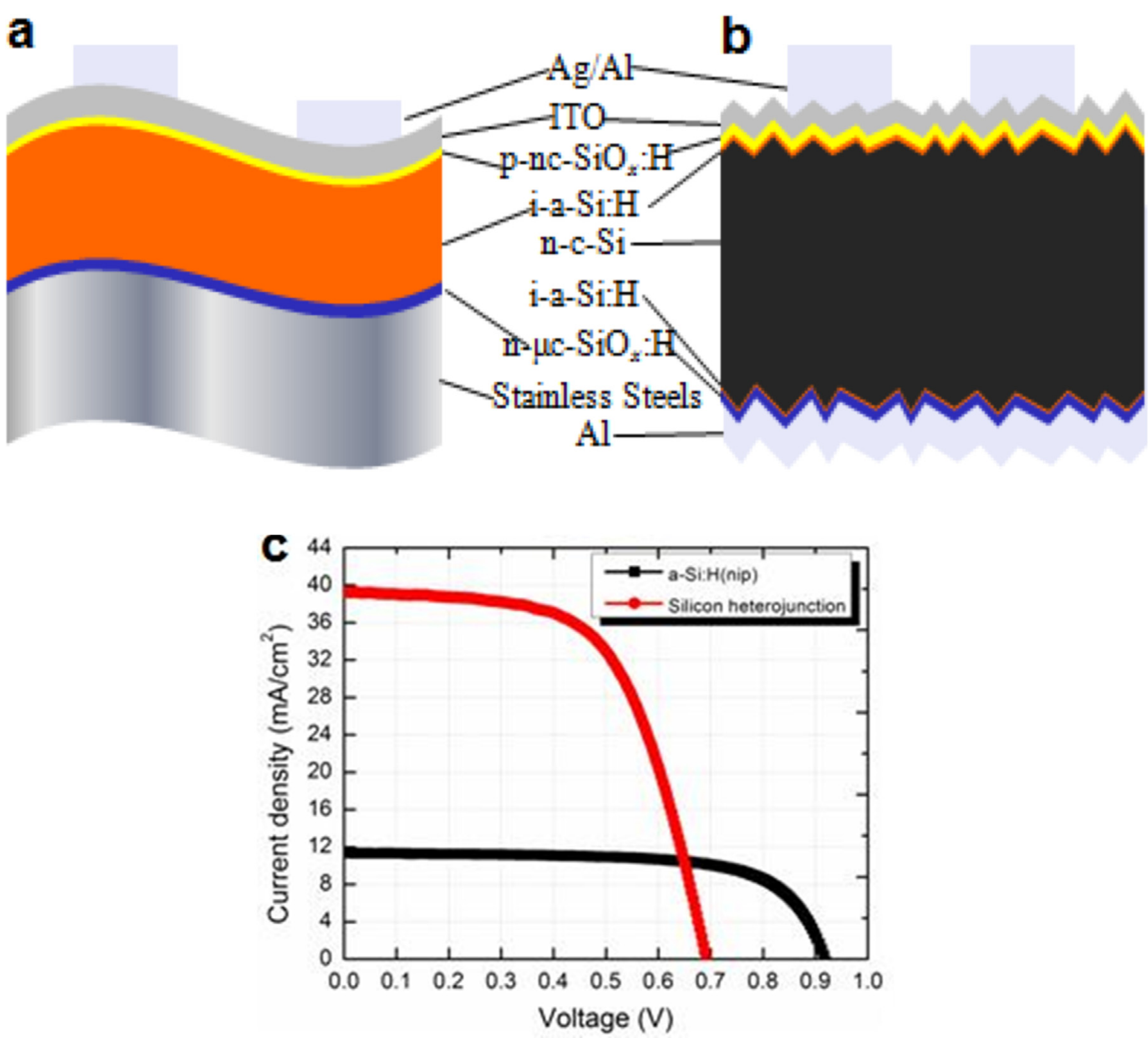

Fig. 1. Schematic illustrations the solar cell structures. (**a**) n-i-p type a-Si:H single junction solar cell, (**b**) HIT single junction solar cell, and (**c**) *J-V* curves of an a-Si:H solar cell and a HIT solar cell.