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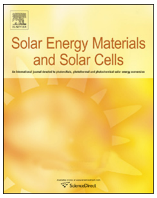

High near-infrared wavelength response planar silicon-heterojunction solar cells

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ABSTRACT

Perovskite/silicon-heterojunction solar cell is a very promising cell structure for using the solar spectrum efficiently and hence improving the energy conversion efficiency. However, perovskite solar cell based on solution technique requires the planar silicon-heterojunction bottom solar cell, which needs a different fabrication process from the textured substrate. In this paper, we developed the high performance planar silicon-heterojunction solar cell by introducing a novel design for the n-type back field and p-type emitter. The results indicate that a wide bandgap and low refractive index nc-SiO$_x$:H for back field improves the open-circuit voltage, fill factor and short-circuit current density by the increased near-infrared long wavelength response. In addition, a nc-Si:H buffer layer between the a-Si:H passivation layer and p-nc-SiO$_x$:H emitter increases the crystallinity in the emitter and then improves device performance further. Combining the developed nc-SiO$_x$:H back field and p-nc-SiO$_x$:H emitter, we achieved an efficiency of 18.77% (Certified 19.1%) on a smooth c-Si wafer. Realization of perovskite/silicon monolithic tandem solar cells with an over 1.7 V output voltage shows the potential application for solar to fuel generation and it also proves that the above strategies are very effective for improving the performance of bottom cell in the tandem solar cells.

1. Introduction

Silicon-heterojunction (SHJ) solar cell is one of the promising solar photovoltaic technologies for high efficient and low cost solar panel production [1]. The cell structure consists of a crystal silicon wafer (c-Si) with hydrogenated amorphous silicon (a-Si:H) alloy passivation layers and doped layers for the emitter and back field junction. Since it takes the advantages of c-Si with high long wavelength response for high photocurrent density and a-Si:H with better passivation effect for high open circuit voltage (V_{oc}), SHJ solar cell has shown higher efficiency than conventional homo-junction c-Si solar cell [2]. Recently, Yoshikawa et al. [3] of Kaneka, Japan, have demonstrated an energy conversion efficiency of 26.3% using a combination of SHJ with interdigitized back contact (IBC), which is approaching the theoretical limitation of 29% [4] and therefore further improvement becomes much more difficult because of such a complicated cell structure. On the other hand, new materials and solar cell structures have been invented and well developed in recent years. As a new comer, perovskite solar cell with an organic/inorganic hybrid structure has shown a very fast efficiency improvement from the original 3.8% [5] in 2009 to recent record of 22.1% [6]. Because of the wider optical band gap of the absorber, perovskite solar cells normally have much larger V_{oc} but smaller short circuit current density (J_{sc}) than SHJ solar cells with a poor spectra response in the long wavelengths. The complementary properties of perovskite and c-Si solar cells make them a perfect match for tandem cell structures with perovskite as the top cell to absorb the short wavelength light and c-Si as the bottom cell to absorb the long wavelength light. A simulation result of White et al. shows that perovskite/SHJ tandem solar cell has the potential to reach over 30% of energy conversion efficiency [7].

In order to make the high efficiency potential become reality, a significant research has been carried out to resolve the issues in perovskite/c-Si tandem solar cell efficiency [8–12]. One limiting factor for the tandem solar cell structure is the requirement for a smooth c-Si wafer substrate. Normally, SHJ solar cells are made on a highly textured c-Si wafer achieved by a chemical etching process with KOH or

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NaOH solution. The pyramidal surface structure provides an effective light coupling and light trapping for high J_{sc}. However, high efficient perovskite top cell is normally deposited using a spin-coating method, which requires a very smooth substrate for maintaining a good uniformity in the perovskite absorber layer [8–12], otherwise, the high textures with pyramidal structures on the c-Si wafer could affect the perovskite top cell performance. In order to attain a high efficiency perovskite/SHJ tandem solar cell, a high performance SHJ solar cell with smooth c-Si is highly desired, which is normally fabricated with different fabrication processes from the conventional SHJ solar cells. Zhang et al. of AIST [13] inserted an a-Si:H buffer layer between the passivation layer and μc-SiO_x:H emitter and increased the V_{oc} to 738 mV and J_{sc} to 33.46 mA/cm^2 on SHJ solar cells based on n-type wafer; Ding and his colleagues at Juelich, Germany, used an intrinsic a-SiO_x:H passivation layer and improved the SHJ solar cell efficiency to 18.5% on a p-type c-Si wafer [14]; furthermore, Pomaska combined n-type microcrystalline silicon carbine (n-μc-SiC:H) and n-type microcrystalline silicon oxide (n-μc-SiO_x:H) as the double-layer window layer to reduce the absorption in the emitter and advanced the efficiency to 18.9% on a p-type c-Si wafer [15].

For the purpose of improving perovskite/SHJ tandem solar cell, the objective of this work is to improve the long wavelength response of SHJ solar cell without introducing additional textured light trapping structure and maintain the ideal V_{oc}. For a perovskite/SHJ tandem solar cell, since the light illuminates the cell from the perovskite top cell, high energy photons are absorbed in the perovskite top cell and the remaining visible and infrared (IR) light are absorbed in the SHJ bottom cell. In this case, the SHJ bottom cell not only needs to have a good V_{oc} but also a high long wavelength response to realize a designed current matching between the top and bottom cells. As mentioned above, the perovskite top cell limits the SHJ solar cell on smooth c-Si wafer, we use polished n-type c-Si wafer without texturing. The improvement in the long wavelength response is achieved by introducing novel design for p-type emitter and the n-type back field layer. As a result, we have made very efficient SHJ solar bottom cells and perovskite/SHJ tandem cells on smooth c-Si wafer.

2. Experimental details

2.1. Thin film silicon deposition and material characterization

The thin film a-Si:H alloy materials were deposited within a multi-chamber cluster plasma enhanced chemical vapor deposition (PECVD) system on Eagle XG glass and Fluorine doped Tin Oxide (FTO) covered glass substrates. Co-planar and sandwich aluminum electrodes were deposited in a evaporation system for conductivity measurements with a Keithley 617 multi-meter. The optical properties of the thin film samples were analyzed using transmission and reflection measurements with a Varian-Cary 5000 spectrometer, including the Tauc optical bandgap and refractive index. The crystallinity of microcrystalline/nanocrystalline films was obtained by fitting the Raman spectra (Renishaw inVia reflex) with three components of c-Si, grain boundary, and a-Si:H phases.

2.2. Planar SHJ solar cell fabrication and characterization

We used polished 280-μm thick n-type c-Si wafer with the resistivity of 1–10 Ω cm as the substrate for SHJ solar cell fabrication. The substrates were cleaned using the standard RCA process following a 1-min etching process in 3% HF solution to remove the native silicon oxide layer. The SHJ solar cell structure is schematically depicted in Fig. 1, which is constructed with Al/Ag front grid(600 nm)/ITO(80 nm)/p-type emitter layer (10 nm)/i-a-Si:H(4 nm)/n-c-Si(280 μm)/i-a-Si:H (5 nm)/n-type layer(20 nm)/Al back contact (600 nm). All of the thin film silicon alloy layers were deposited in the multi-chamber PECVD system with various gas mixtures. Hydrogen diluted SiH_4 was used for the a-Si:H passivation layer; PH_3 and $B(CH_3)_3$ were used as the doping gases for the n-type back field layer and p-type emitter, respectively; and CO_2 as the oxygen source for the silicon oxide layers. The ITO layer, metal grids, and back contact were all made with thermal evaporation. The solar cell area of 0.53 cm^2 was defined by the shadow mask for ITO deposition. The solar cell performance was characterized by the current density versus voltage (J-V) measurements under an AM1.5 solar simulator (WXS-156S-L2, AM1.5GMM) with 100 mW/cm^2 at 25 °C. The external quantum efficiency (EQE) spectra were measured using a QEX10 PV system and the J_{sc} was calculated by the integral of measured EQE and the AM1.5 solar spectrum.

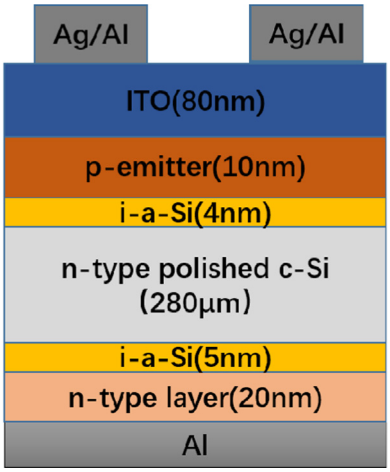

Fig. 1. Schematic of planar SHJ solar cell.

3. Results and discussion

3.1. Back field effect on the optical performance of devices

As shown in Fig. 1, the c-Si surface was first passivated using a thin a-Si:H layer on both sides, the effectiveness of a-Si:H passivation was optimized by systematically varying the hydrogen dilution (Fig. S1), process pressure/RF power (Fig. S2), and thickness (Fig. S3).

From the EQE curves in Fig. S4, it first notes that the short wavelength response is still lower than expected for a high efficiency SHJ solar cell. Two reasons have been indentified for the poorer short wavelength response: one is the absorption in the emitter and a-Si:H passivation layer and the other is the high reflection. Because the light illuminates the solar cell from the p-side, it has to pass through the ITO, p-type emitter, and a-Si:H passivation layer before reaching the c-Si absorber for photocurrent generation. The photons with the energy higher than the a-Si:H bandgap (1.70–1.75 eV) are partially absorbed in the emitter and a-Si:H passivation layers, which do not produce photocurrent but the photogenerated carriers recombine there. Correspondingly the EQE response for the wavelength shorter than ~ 750 nm is lowered by the parasitic absorption. In addition, the smooth surface of the c-Si results in a high reflectance because of the quarter wavelength anti-reflection ITO coating does not reduce the reflectance in the very short and very long wavelength regions except for the middle wavelength around 550 nm. The high reflectance in the short wavelength adds an additional factor for the low short wavelength response. On the other hand, the long wavelength photons have a much lower absorption coefficient; they pass the emitter and the a-Si:H passivation layer to generate photocurrent in the c-Si absorber, and some photons even passes through the thick c-Si absorber to reach the back field region, where the i-a-Si:H/n-layer and n-layer/Al interfaces reflect most of the light back to the absorber for second time absorption, but some are absorbed in the back a-Si:H passivation layer and the back field n-layer. Therefore, the back field contact is also functioning as a