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Effect of Buffer Structure on the Performance of a-Si:H/a-Si:H Tandem Solar Cells

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ABSTRACT

The study focuses on the influence of the hydrogenated amorphous silicon carbide (a-SiC:H) buffer layer in hydrogenated amorphous silicon (a-Si:H) single-junction and tandem thin-film solar cells. By increasing the undoped a-SiC:H buffer layer thickness from 6nm to 12nm, the J_{SC} in single-junction cell was significantly improved, and the efficiency was increased by 4.5%. The buffer layer also effectively improves the efficiency of the a-Si:H/a-Si:H tandem cells by 7% as a result of the increase in open-circuit voltage (V_{OC}) and short-circuit current (J_{SC}). Although the bottom cell absorbs less short-wavelength photons, the wider-bandgap doped and buffer layers were still necessary for improving the cell efficiency. Presumably, this is because these wider-bandgap layers allow more photons to reach the bottom cell. Also, they can reduce interface recombination.

INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) has received much attention due to its superior properties for the thin-film solar cells. The high absorption coefficient of a-Si:H allows it to absorb light with less material. The bandgap around 1.75eV also makes it suitable for the effective absorption of the solar spectrum. However, the Staebler-Wronski effect (SWE) [1] influences the long-term stability of the solar cells, resulting in a decrease in the cell efficiency [2]. The amount of the degradation depends on the material quality and the film thickness. By the use of a-Si:H/a-Si:H tandem structure, the absorber is divided into two devices [3]. The thinner absorber not only reduces the degree of SWE, but also creates a stronger build-in electric field to assist the carrier transport. Wieder et al. [4] had reported an initial cell efficiency of 9.2% with a relative decrease of 8% after 900 hours light soaking due to a more effective carrier extraction in thinner undoped layers. Furthermore, other materials with lower bandgaps, such as hydrogenated amorphous silicon germanium (a-SiGe:H) or hydrogenated microcrystalline silicon (μc-Si:H) can be used in the bottom cells. However, a-SiGe:H uses costly germane and μc-Si:H requires longer deposition time. As a comparison, the a-Si:H/a-Si:H solar cell has a lower production cost.

A high efficiency a-Si:H single-junction thin-film solar cell normally contains a wide-bandgap window layer to allow more high energy photons to be absorbed in the undoped layer. However, the bandgap difference between doped and undoped a-Si:H at the p/i interface hinders the hole transportation [5]. A wide-gap undoped layer was therefore used to accommodate the band offset. Such a buffer layer also significantly reduces the p/i interface recombination, prohibits the electron from moving into p-layer [6] and may prevent the boron diffusion into absorber. As a result, the buffer layer can significantly improve the V_{OC}, accompanied by the increases in J_{SC}, fill factor (FF) and efficiency. In an a-Si:H/a-Si:H tandem solar cell, although the two absorber have identical or similar bandgaps, the bottom cell still absorbs less high energy photons than the top cell. Replacing the material of the window layer (in the bottom cell) to doped a-Si:H may have a better electrical property due to more effective doping. To investigate whether the wide-bandgap material was needed in the bottom cell, the study focused on the properties of the a-SiC:H material and the structure of the tandem solar cell.

EXPERIMENT

In this work, the devices were prepared in a 27.12MHz plasma-enhanced chemical vapor deposition (PECVD) system on a SnO:F glass in a superstrate configuration. A gas mixture of SiH_4 and H_2 was used to deposit undoped a-Si:H. Undoped a-Si:H film with thicknesses ranging from 40nm to 80nm were used in the top cell. The p-type and n-type layers were achieved by introducing B_2H_6 and PH_3, respectively, during deposition. With the addition of CH_4, doped or undoped a-SiC:H thin-film were obtained. The p-type a-SiC:H thin-film had a conductivity of $1.48x10^{-5}$S/cm with an optical bandgap of 1.95eV. By modulating the CH_4 flow rate, the optical bandgap of the undoped a-SiC:H film can be altered. Amorphous a-SiC:H p-layer and undoped buffer layer were used in the top or the bottom cell, as can be seen in Fig.1. For the study of replacing the a-SiC:H p- and buffer layer by a-Si:H p-layer in the bottom cell, the thin-film with a conductivity of $1.12x10^{-5}$S/cm with an optical bandgap of 1.75eV was used. Considering the light-induced-degradation, a fixed absorber thickness of 300nm was used in the bottom cell. No particular tunneling junction between top and bottom cell was used. A back reflector consisted of TCO and silver was also used to enhance the reflection of long-wavelength photons.

The optical bandgap of the a-SiC:H thin-film was derived from the UV/VIS/IR spectrometer. The electrical properties of the thin-film and the devices were characterized with an AM1.5G illuminated I-V measurement system and a quantum efficiency (QE) instrument.

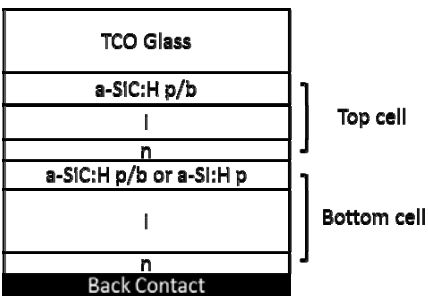

Figure 1. Schematic diagram of the a-Si:H/a-Si:H solar cell structure

RESULTS AND DISCUSSION

We first studied the single-junction cells from the optimization and characterization of the undoped a-SiC:H thin-films. The bandgap of the a-SiC:H film can be changed by varying the carbon content in the film. Instead of stoichiometric composition of the crystalline SiC, the a-

SiC:H material used here has a much lower carbon content, due to the consideration of electrical and optical properties. Fig.2 shows the effect of methane-to-silane flow rate ratio on the conductivity and the bandgap. As the flow ratio in the gas phase increased from 0 to 1.5, the bandgap increased from 1.80eV to 2.04eV, indicating an increased incorporation of C in the film. Accompanied with the increasing bandgap, the photo-conductivity significantly decreased mainly due to the increasing defects. Besides, fewer photons were able to be absorbed by the materials with the higher bandgap. The dark-conductivity did not show obvious decrease which can also be due to the increasing defect density induced by the carbon [7]. The selection of the a-SiC:H material should consider the trade-off between electrical and optical properties based on conductivity and bandgap, respectively. In this study we use the a-SiC:H with methane-to-silane flow ratio of 0.5.

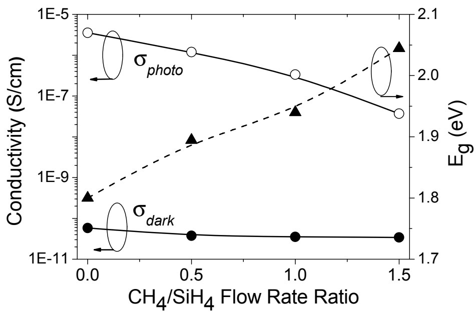

Figure 2. Effect of the methane-to-silane flow rate ratio on the conductivity and the bandgap

The buffer layer with thickness of 6nm has a bandgap of 1.89eV, slightly smaller than the p-type layer which was 1.95eV. The 12nm buffer layer had changed bandgaps which were achieved by decreasing the methane flow rate during deposition. Although the a-SiC:H layer was located at the front side of the device, a total enhancement was observed in the range from 350nm to 700nm, as shown in Fig. 3. This indicates that the wide-bandgap material not only allows more short-wavelength photons be absorbed, but also assisted the transport of carriers generated near the n/i interface. The increase in the EQE measurement reflected the increase in J_{SC} and FF while V_{OC} shows no significant change, compared to the study which has significant improvement in V_{OC} [6]. By optimizing the thickness of the buffer layer with compromised bandgap and conductivity, a relative increase of 4.5% in single-junction cell efficiency from 7.95% to 8.31% was obtained. In this study we achieved a higher efficiency with buffer layer thickness of 12nm. Further optimization was carried out to achieved a single-junction a-Si:H solar cell with efficiency of 9.45%, with J_{SC}=14.39mA/cm^2, V_{OC}=0.90V and FF of 73.33% [8].

On the next we fabricated the tandem device based on the previous single-junction cell structure. The a-Si/a-Si tandem structure was fabricated based on the structure of the single-junction solar cell. In order to obtain better solar cell efficiency, the current generated from the top cell should match to that from the bottom cell because of the limitation of a series connection. With the increasing thickness, the generated photo-current in the top cell should increase, while the current generated in the bottom cell decreased. As the two current are perfectly the same, the whole device would have the highest efficiency.

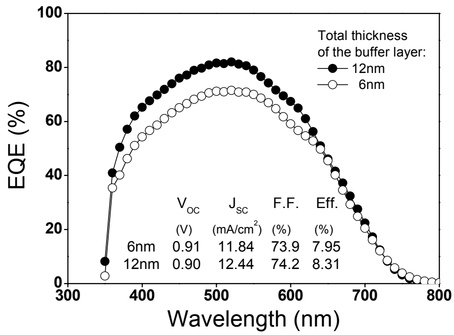

Figure 3. External quantum efficiency measurement of the cells prepared with different thicknesses of a-SiC:H buffer layer.

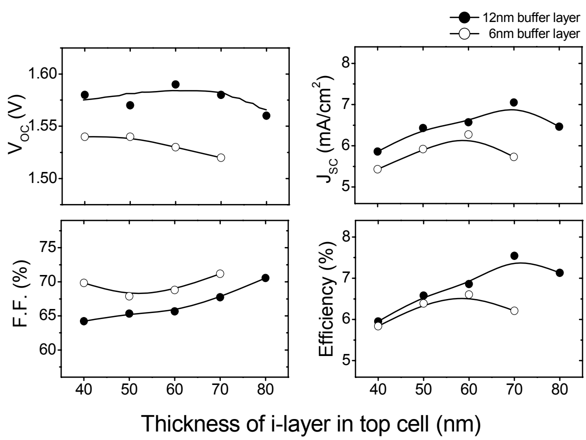

Figure 4. Effect of the i-layer thickness in the top cell on the performance of the tandem cells with different buffer layer thicknesses.

Fig. 4 shows the effect of the i-layer thickness in top cell on the cell performance with 6nm and 12nm buffer layer thicknesses, while the thickness of undoped a-Si:H in the bottom cell was kept at 300nm under the consideration of degradation. Although the V_{OC} has no improvement in the single-junction cell, significant improvement of V_{OC} in the tandem cell was observed. There was decrease in fill factor due to the absence of tunneling recombination junction [9], but the increase of J_{SC} accompanied with increased V_{OC} improved the overall efficiency by 7.0%. The cell with 12nm-thick buffer layer in both top and bottom cell has an efficiency of 7.54% with i-layer thickness of 70nm in top cell, compared to the cell with 6nm buffer layer and 60nm i-layer having an efficiency of 7.05%. The thicker i-layer required for the top cell having 12nm buffer layer may be due to the reduction of build-in field affected by the insertion of the undoped a-SiC:H, while the increased thickness of a-SiC:H in the bottom cell shows less influence due to small portion in the 300nm undoped a-Si:H.

In Fig. 4, the FF gradually increased even if the thickness of the top cell was thicker than the matched one. This behavior in FF is only observed in cell without the tunnel junctions. The normal behavior in FF was observed in other experiments where tunnel junctions were employed. Although we do not understand the nature of this phenomenon, we believe this is related to the absence of the tunnel junctions. Further experiments are needed to investigate such effect.

The comparison of EQE measurement from the cells having different buffer structures is shown in Fig. 5. The i-layer thickness in the bottom cell was also fixed at 300nm with 60nm or 70nm i-layer thickness in the top cell, depending on a better current matching. As the buffer thickness increased from 6nm to 12nm for the cell having a-SiC:H in both top and bottom cell, the current density increased. As a result the total quantum efficiency increased with a maximum of over 80%.

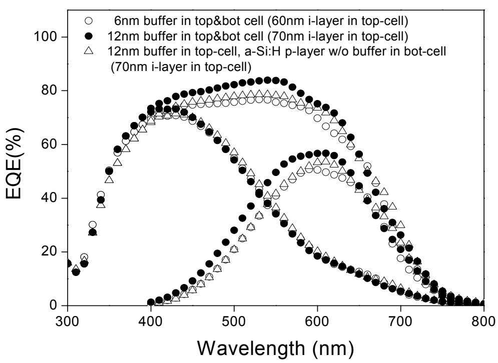

Figure 5. EQE measurement of the cells with 6nm and 12nm a-SiC:H buffer layer in the top and the bottom cell, and the cell without buffer layer in the bottom cell.

We have also made a cell with bottom cell contained p-type a-Si:H only (also without a-SiC:H buffer layer) to see if the a-SiC:H was still necessary in the bottom cell, since the wide-bandgap a-SiC:H mainly increases the short-wavelength incident light and the buffer layer may act as a resistor in such device. The result shows that the bottom cell with a-SiC:H p-layer and 12nm buffer layer still generated a higher current. Compare to the cell with 6nm a-SiC:H buffer, the cell composed of no a-SiC:H in the bottom cell had no apparent improvement. The carrier generated in the bottom cell with shorter wavelength decreased and showed similar result with cell having 6nm buffer. The result indicates the wide-bandgap window layer can still benefit the absorption of the bottom cell to have a higher current density. Part of the contribution may also arise from the reduced recombination at p/i interface by the insertion of high quality a-SiC:H.

CONCLUSIONS

We have found by increasing the undoped a-SiC:H buffer layer thickness from 6nm to 12nm, the single-junction cell performance improved significantly in J_{SC}, and the overall efficiency by 4.5%. The buffer layer also effectively improves the efficiency of the a-Si:H/a-Si:H tandem cell by 7% because of the increased V_{OC} and J_{SC}. Although the bottom cell absorbs less short-wavelength photons, the wide-bandgap doped and buffer layers were still necessary for improving efficiency which may be due to the absorption of short-wavelength photons and the advantage of reducing interface recombination.

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