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Research Article

Optimization of Recombination Layer in the Tunnel Junction of Amorphous Silicon Thin-Film Tandem Solar Cells

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The amorphous silicon/amorphous silicon (a-Si/a-Si) tandem solar cells have attracted much attention in recent years, due to the high efficiency and low manufacturing cost compared to the single-junction a-Si solar cells. In this paper, the tandem cells are fabricated by high-frequency plasma-enhanced chemical vapor deposition (HF-PECVD) at 27.1 MHz. The effects of the recombination layer and the i-layer thickness matching on the cell performance have been investigated. The results show that the tandem cell with a p^+ recombination layer and i_2/i_1 thickness ratio of 6 exhibits a maximum efficiency of 9.0% with the open-circuit voltage (V_{oc}) of 1.59 V, short-circuit current density (J_{sc}) of 7.96 mA/cm^2, and a fill factor (FF) of 0.70. After light-soaking test, our a-Si/a-Si tandem cell with p^+ recombination layer shows the excellent stability and the stabilized efficiency of 8.7%.

1. Introduction

Amorphous silicon (a-Si)/a-Si tandem solar cells have attracted extensive interest among solar cell because of the less light-induced degradation [1, 2] (Stabler-Wronski effect) compared to their single-junction solar cell counterparts. The n-p junction between the two subcells is often referred to as a tunnel junction but actually functions as a recombination junction in electrically connecting the two p-i-n junctions of the tandem structure. For high stabilized efficiency tandem cell applications, a good n/p junction must have very high recombination rates, negligible optical absorption, and an ohmic characteristic with a low series resistance in order to improve the carrier transport [3–6]. Various recombination layers, such as a-SiC:H [7], metal oxides [8], microcrystalline n^+ layer [9], and n^+/p^+ recombination layer [10] have been introduced between the n and p layers to promote carrier recombination.

The thickness of intrinsic- (i-) layer of individual subcell is another key parameter because of the current matching limitation imposed by series connection. In addition, reducing the i-layer thickness of top cell as possible as it is important to stabilize against light degradation [11, 12].

In this paper, we use a p^+ recombination layer as the recombination layer inserted in a tandem solar cell to investigate the effect on the cell performance. Furthermore, the tandem cells with different i-layer thickness matching ratio are also fabricated and their photovoltaic characteristics are also discussed.

2. Experimental

In this study, we prepared double-junction (a-Si/a-Si) solar cells by high-frequency (27.1 MHz) plasma-enhanced chemical vapor deposition (HF-PECVD). The HF-PECVD reac tion chamber is equipped with a load-lock for the transport and placement of the substrate into the chamber including a substrate holder, and a system with temperature control. The size of chamber was 20×20 cm^2, and the electrode distance ranged from 7 mm to 40 mm. We fabricated tandem cells without recombination layer (p_1-b_1-i_1-n_1-p_2-b_2-i_2-n_2),

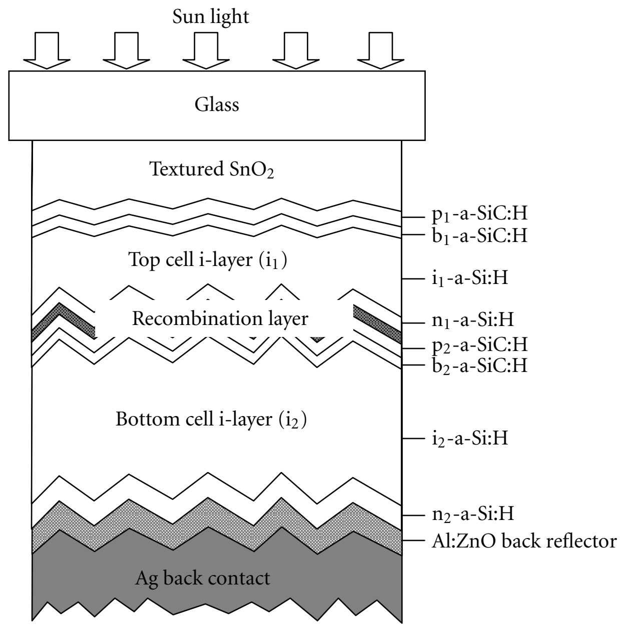

Figure 1: Schematic structure of an a-Si/a-Si tandem solar cell.

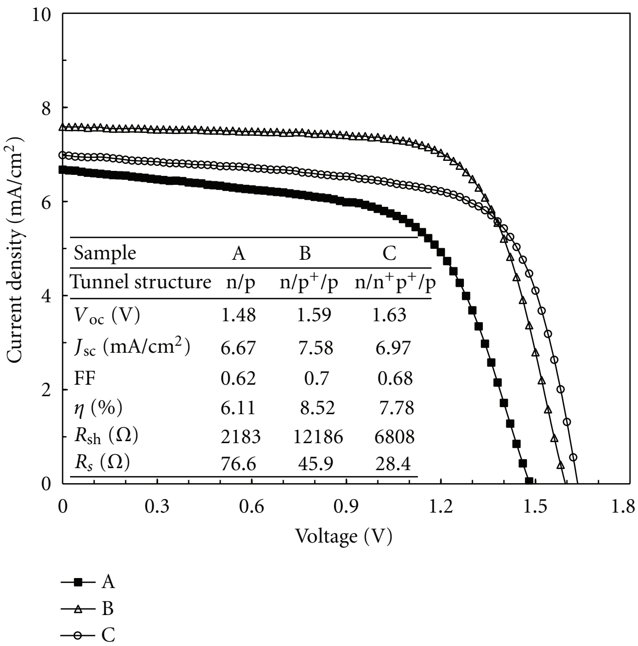

Figure 2: *I-V* characteristics of sample A, B, and C. Sample A is with the standard n/p junction; sample B has the p^+ recombination layer; sample C has the n^+/p^+ double recombination layer.

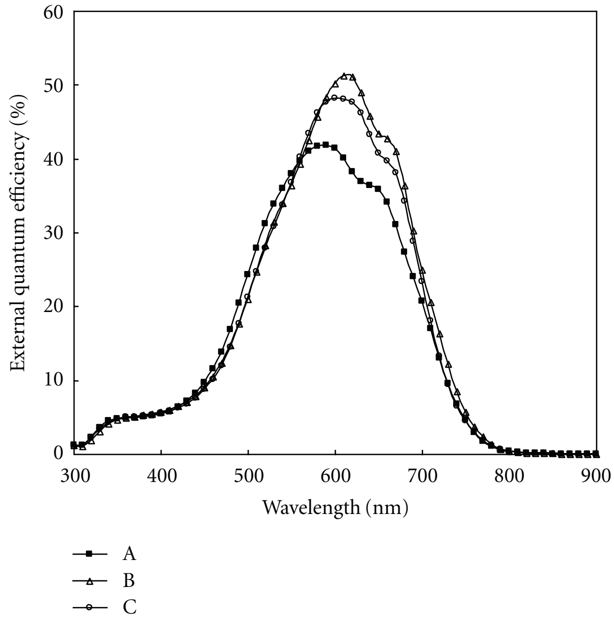

Figure 3: Measured QE of solar cells of sample A, B, and C. Sam-ple A is with the standard n/p junction; samples B has the p^+ recombination layer; sample C has the n^+/p^+ double recombination layer.

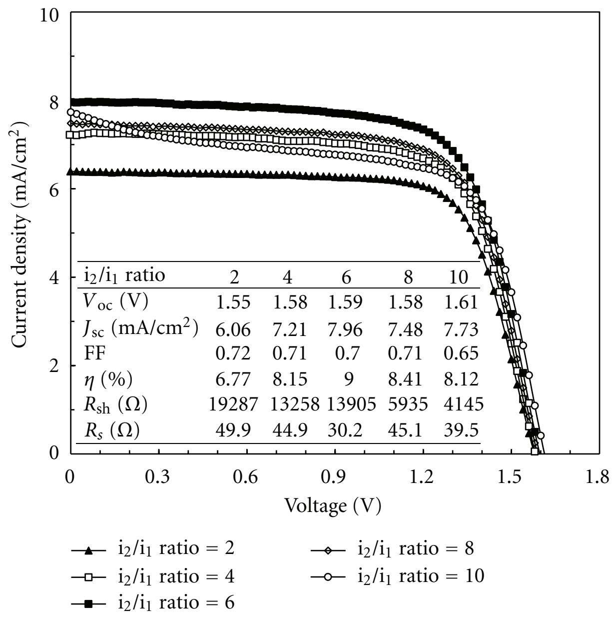

Figure 4: *I-V* characteristics of a-Si/a-Si tandem solar cells with different i_2/i_1 ratio.

with p^+ recombination layer and with n^+/p^+ double recombination layers inserted between two subcells, which were designated as sample A, sample B, and sample C, respectively. The schematic structure is shown in Figure 1. The substrate used in this paper was SnO_2-coated glass (Asahi U-type). The substrate temperature was fixed at 200°C. The detailed process conditions are summarized in Table 1. An a-SiC:H buffer layer is necessary for making the energy band gap between p-a-SiC:H layer and i-a-Si:H layer much smoother and reducing the recombination at the p/i interface to enhance the open-circuit voltage. To optimize the current matching, we set five thickness ratios of i-layer in the bottom cell to i-layer in the top cell of 2, 4, 6, 8, and 10 individually. The *I-V* characteristics of the device were measured under an AM1.5G solar simulator. Quantum efficiency (QE) was

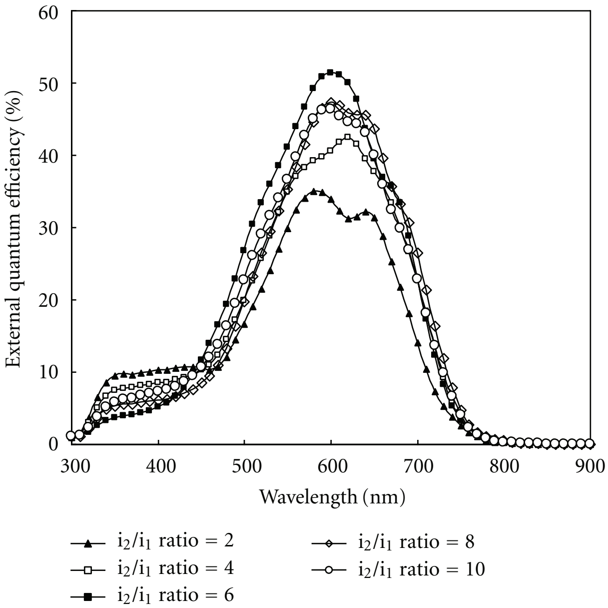

Figure 5: Measured QE of solar cells with different i_2/i_1 ratio.

Table 1: The deposition conditions of intrinsic layer of the tandem solar cell.

Parameter	Value
Power (W)	10
Pressure (Pa)	90
E/S distance (mm)	30
Substrate temperature (°C)	200
SiH_4 flow rate (sccm)	40
H_2 flow rate (sccm)	160
i_2/i_1 thickness ratio	2–10

measured for a wavelength range of 300 to 900 nm. Cross-section micrographs of the solar cell were obtained by transmission electron microscopy (TEM). The light soaking test was performed at the open circuit condition under one-sun light intensity using a metal halide lamp at 50°C for 500 h.

3. Results and Discussion

Figure 2 shows the *I-V* characteristics of sample A, sample B, and sample C. It can be seen that the open-circuit voltage (V_{oc}) increases in the case of adding either p^+ recombination layer or n^+/p^+ double recombination layers. For the short-circuit current density (J_{sc}), the sample A, which is without recombination layer, does have a rectifying property, resulting in a reduction in J_{sc} [10]. The sample B shows the highest J_{sc} due to it not only has the smallest series resistance (R_s) offering a good ohmicity of the tunneling junction, but also the largest shunt resistance (R_{sh}). For the sample C, the n^+/p^+ double layer causes a buildup of trapped holes on the p^+ side and electrons on the n^+ side, and hence yields a lower J_{sc} compared to the sample B. From our result, the best cell conversion efficiency of 8.52% occurs when the p^+ recombination layer is used.

The variation in the previous J_{sc} result is also reflected in the QE measurements, shown in Figure 3. The QE curves of these samples remain the same in the short-wavelength region but evidently vary in the long wavelength region, implying that the adding recombination layer could mainly improve the absorption at long wavelength.

Figure 4 shows the experimental *I-V* characteristics of the double-junction solar cells subject to different i_2/i_1 thickness ratio. It can be seen that the V_{oc} almost maintains a stable value of 1.59 V, approximately equaling to the sum of the V_{oc} of the two subcells, showing a good series connection. The J_{sc} increases from 6.06 to 7.96 mA/cm^2 with increasing the i_2/i_1 thickness ratio from 2 to 6, and then it drops to a lower value with further increasing the ratio. This result can be explained by the QE result, as shown in Figure 5. The tandem cell with an i_2/i_1 thickness ratio of 6 presents the highest QE response, showing the optimum current matching. By using the optimum i_2/i_1 thickness ratio, a conversion efficiency of 9% is obtained.

Figure 6(a) shows TEM cross-sectional images of the tandem cell with the p^+ recombination layer. The AZO back reflectors layer of 80 nm and Ag layer of 300 nm on the a-Si:H solar cell can be observed demonstrates the whole cross-section morphology. The photograph depicting the interface between p-layers and SnO_2 (TCO) of Asahi (U-type) substrate deposited the high-resolution TEM (HR-TEM) is shown in Figure 6(b), and Figure 6(c) demonstrates the TRJ ($n/p^+/p$) and recombination layer (p^+-layer) between top and bottom cells. In general, a better interface treatment and uniform films are important factors for double-junction solar cells. It seems that each layer and interface of cells as shown Figure 6 is deposited densely and uniformly. Therefore carriers are able to travel longer path thus good for the conversion efficiency.

Figure 7 demonstrates the maximum output power of the a-Si/a-Si tandem solar cells with the p^+ recombination layer and the thickness ratio of 6 as a function of the exposure time. The relative power is also shown for the convenience of observing the degradation. Only very little decrease in power (less than 5% degradation) is observed, showing that the a-Si/a-Si tandem solar cell is more stable than a traditional single junction a-Si cell. This result can be attributed to a thinner i-layer (50 nm) of the top sub-cell compared to that 300 nm thickness i-layer of the single-junction solar cell, might leading to a reduction in escape of hydrogen atoms from Si matrix.

4. Conclusions

In this paper, the effects of the recombination layer and the i-layer thickness matching on the cell performance have been investigated. The results show that inserting the recombination layer can increase the V_{oc} and J_{sc}. Furthermore, the i-layer thickness ratio strongly affects the J_{sc}, and the i-layer of bottom sub-cell thicker than that of top sub-cell by a factor

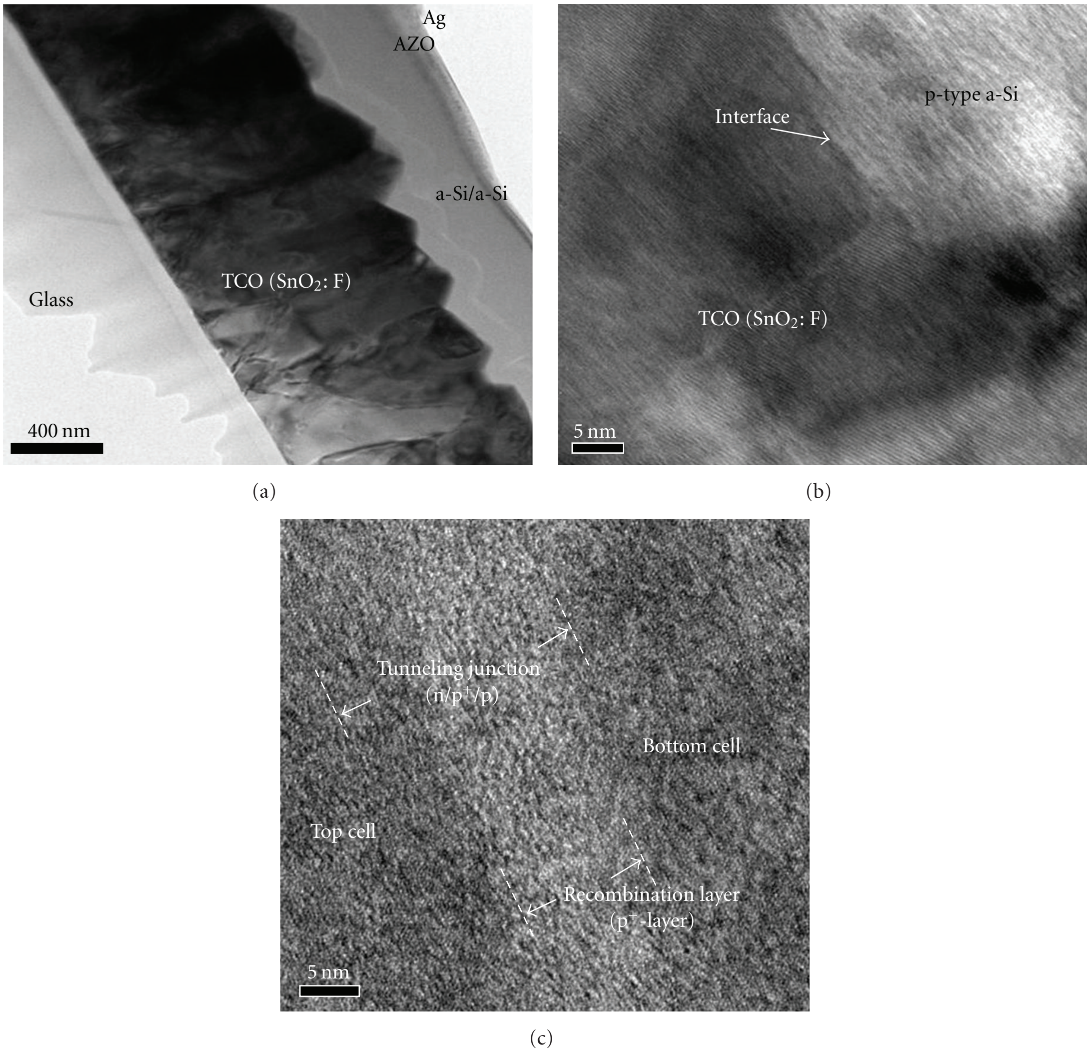

Figure 6: Cross-sectional transmission electron micrographs of (a) a-Si/a-Si tandem cell, (b) TCO/p interface, (c) n/δ(p^+)/p junction.

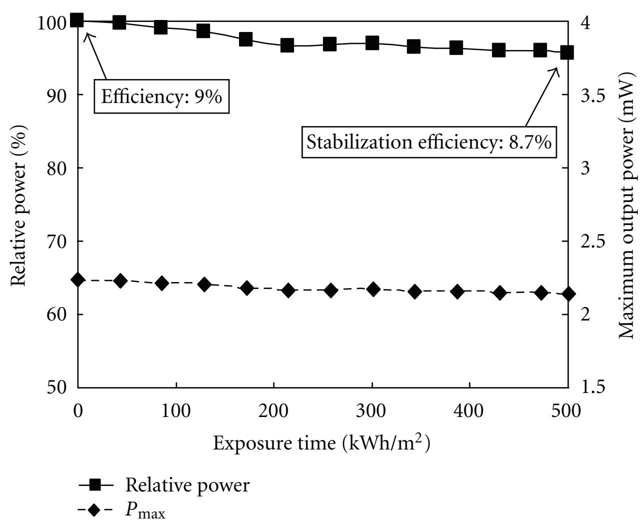

Figure 7: The maximum output power and relative power of the a-Si/a-Si tandem solar cells with the p^+ recombination and the thickness ratio of 6 as a function of the exposure time.

of 6 is found to be the optimum thickness matching. Finally, an initial efficiency of 9.0% and the stabilized efficiency of 8.7% are obtained, showing the good stability compared to a typical single-junction a-Si:H solar cell.

Acknowledgments

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