TRIPLE-JUNCTION A-SI SOLAR CELLS WITH HEAVILY DOPED THIN INTERFACE LAYERS AT THE TUNNEL JUNCTIONS

W. Wang, H. Povolny, W. Du, X.B. Liao and X. Deng
Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606 USA

ABSTRACT

Triple-junction a-Si based solar cells, having a structure of SS/Ag/ZnO/n^+/n/b/a-SiGe-i/b/p/p^+/n^+/n/b/a-SiGe-i/b/p/p^+/n^+/n/a-Si-i/p/p^+/ITO, are fabricated at the University of Toledo using a multi-chamber, load-locked PECVD system. We studied the effect of heavily doped p^+ and n^+ layers deposited at the tunnel junction interfaces between the top and middle component cells and between the middle and bottom component cells on the efficiency of triple-junction solar cells. Preliminary results show that thin, ~ 1nm, interface p^+/n^+ layers improve the solar cell efficiency while thicker interface layers, ~4nm thick, cause the efficiency to decrease. Incorporating the improved interface layers at the tunnel junctions, as well as earlier improvements in the intrinsic layers, the p-i interface in terms of reducing the band-edge offset, and the a-SiGe component cells using bandgap-graded buffer layers, we fabricated triple-junction solar cells with 12.71% efficiency in the initial state and 10.7% stable efficiency after 1000 hours of 1-sun light soaking. Samples sent to NREL for independent measurements show 11.8% total-area (or 12.5% active-area) initial efficiency.

INTRODUCTION

Triple-junction solar cell structure have been studied and used extensively to deposit high-efficiency a-Si based solar cells. Using a triple cell structure, United Solar Systems Corp. fabricated a-Si/a-SiGe/a-SiGe solar cells with 13% stabilized efficiency [1]. In such a triple-junction, two-terminal structure, the tunnel junction between the doped layers of neighboring component cells are formed due to the high concentration of recombination centers from the dangling bond defects in the doped a-Si materials. For this reason, the doped layers at the tunnel junctions are usually made thicker and/or with higher doping concentrations than those for single-junction solar cells [2]. However, a thicker doped layer would result in an optical loss and a higher doping concentration would result in a reduced bandgap, consequently, a lower Voc. In an earlier work [3], doping graded p-layer was studied in an n-i-p-n test structure. It was found that a p-layer with higher doping near the n-layer and lower doping near the i-layer leads to improved efficiency compared with a p-layer with constant doping [3]. In this work, we investigate the impact of inserting heavily doped thin interface layers at the tunnel junction to enhance the recombination of carriers from neighboring component cells.

EXPERIMENTAL

The structure of triple-junction a-Si based solar cell fabricated in this study is SS/Ag/ZnO/n^+/n/b/a-SiGe-i/b/p/p^+/n^+/n/b/a-SiGe-i/b/p/p^+/n^+/n/a-Si-i/p/p^+/ITO, where SS is stainless steel foil substrate, p^+ and n^+ are heavily doped interface layers, and /b/ on both sides of a-SiGe i-layers are bandgap graded buffer layers. All of the semiconductor layers were deposited using University of Toledo (UT)'s multiple-chamber PECVD system. The substrate coated SS is provided by Energy Conversion Devices, Inc. (ECD) and United Solar. ITO is deposited at UT using rf sputtering from a ITO target in Ar ambient. The solar cells were characterized at UT using a Xe-lamp solar simulator and a quantum efficiency measurement system with optical and electrical bias capability, allowing us to measure the QE of component cells in a triple-junction two-terminal stack. Detailed description of the experimental details can be found in our earlier reports [4].

RESULTS AND DISCUSSIONS

Heavily doped p^+ and n^+ interface layer at the tunnel junctions

Table 1 shows the I-V characteristics of a series of four triple-junction solar cells having a structure SS/Ag/ZnO/n_1^+/n_1/b/a-SiGe-i_1/b/p_1/p_1^+/n_2^+/n_2/b/a-SiGe-i_2/b/p_2/p_2^+/n_3^+/n_3/a-Si-i_3/p_3/p_3^+/ITO, where p_1^+/n_2^+ and p_2^+/n_3^+ interface layers are varied while all other layers are essentially kept unchanged for the set of devices. These heavily doped layers were deposited using a doping ratio of BF_3:SiH_4=1.7:1 for the p^+ layer and PH_3: SiH_4=1:10 for the n^+ layer. The deposition rates for the p^+ and n^+ layers are estimated to be 0.3 Å/s and 1 Å /s, respectively.

As we see from the Table, GD846 was fabricated without heavily doped interface layer and is used here as a reference sample. Compared with GD846, GD840 (made with 10 s p^+/n^+ layers) show an improvement in both the J_{sc} and FF. More devices will be fabricated to confirm that there is indeed an improvement in the current when thin p^+/n^+ layers are inserted at the tunnel junctions. The loss of current in GD846, if further confirmed, would likely be due to an insufficient amount of recombination centers near the tunnel-junction interface, hindering photo-generated carriers from flowing to the tunnel junction to recombine. However, when thicker p^+ and n^+ layers, with 20 s or longer deposition time, are used, V_{oc} drops significantly, from 2.31 V to 2.22 V. There are two possible reasons for this Voc drop. First, since the bandgap of a-Si decreases with increased doping, the effective bandgaps of the doped layers, p/p^+ and n/n^+, are reduced when the p^+ and n^+ layers are made thicker, resulting in a reduced built-in potential. Second, when the heavily doped layers are too thick, holes from p_1 (p_2) could fall into deep traps in p_1^+ (p_2^+) while electrons from n_2 (n_3) could fall into deep traps in n_2^+ (n_3^+); and these traps could be 50 Å apart, as in the case of GD854. These trapped charges could form a reversed electrical field at the p^+/n^+ interface, reducing the total voltage of the triple cell. These trapped charges also generate potential barriers at the p/p^+ and n/n^+ interfaces, hindering the flow of carriers toward the p^+/n^+ interface, resulting in reduced current, as reflected in the J_{sc} of GD854. The loss in FF in GD854 could have two contributions. First, it could be from these potential barriers indicated above. Second, the additional optical absorption by the thicker p_2^+/n_3^+ layers and p_1^+/n_2^+ would reduce the current of the middle and bottom component cells, respectively, causing the triple cell to be more limited in current, at the power point, by the middle or bottom cell which has poorer FF than the top component cell. This results in a drop in the overall triple-cell FF.

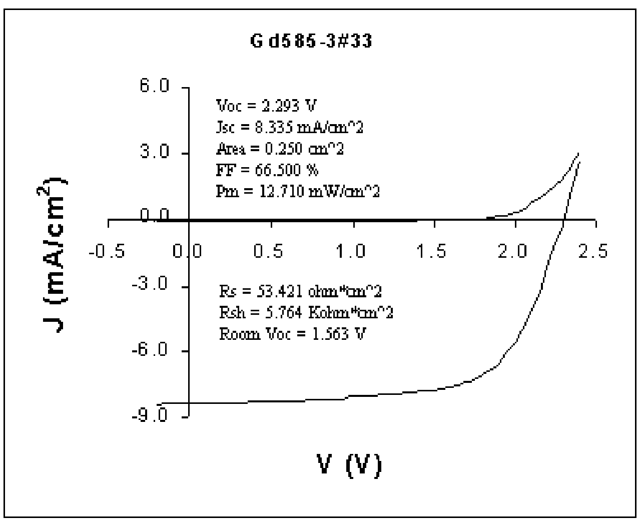

Figure 1 IV curve of a UT fabricated triple cell, showing 12.7% initial, active-area efficiency.

Fabrication of Triple-Junction a-Si Solar Cells

Incorporating optimized p^+/n^+ layers at the tunnel junctions, as well as other recent improvements related to our triple-cell fabrication including: 1) an improved intrinsic a-Si:H top cell i-layer made at low temperature and very high hydrogen dilution (see IV performance data of component cells in Table 2); 2) improved a-SiGe component cells using bandgap graded buffer layers [5] (See IV data in Table 2) ; 3) optimized nanocrystalline p-layer deposition conditions to reduce the band-edge offset at the p-i interfaces for component cells with different i-layer bandgaps [6]; and 4) a careful analysis of the light spectrum of our solar simulator and improved the current matching among component cells, we achieved the fabrication of a-Si/a-SiGe/a-SiGe triple cells with 12.7% initial efficiency. Figure 1 shows the IV curve of the 12.7% triple cell, GD585. The performance for the triple cell is V_{oc}=2.29V, J_{sc}=8.34 mA/cm^2, FF=66.5% and the initial efficiency is 12.7%.

Figure 2 shows the quantum efficiency curves of the component cells in this triple cell. At the top of Figure 2, we show the calculated short circuit currents of the component cells under both UT simulator and the AM1.5 global spectrum. Since the Xenon lamp spectrum does not match exactly the AM1.5 global spectrum, different short circuit currents were obtained when being calculated using different spectrums. It should also be pointed out that the top cell current was calculated with wavelength longer than 370 nm. Therefore, the actual current should be larger than the current of shown in the figure for top cell by about 0.3 mA/cm^2 according to our estimate.

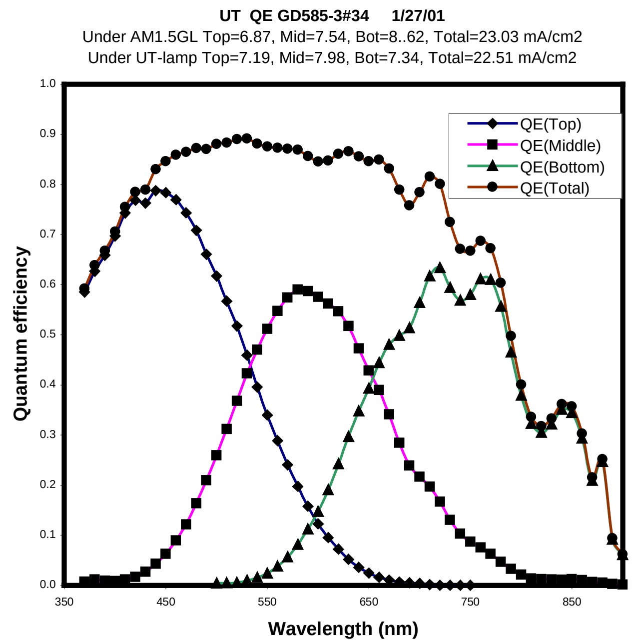

Figure 2 Quantum efficiency curve of 12.7% cell (GD585) showing the QE for top, middle and bottom cells. The figure also shows the short circuit current under UT simulator and AM1.5 spectrum.

Some triple cells fabricated at UT were sent to NREL for independent measurements. Table 3 shows the measurement for GD585 measured at NREL and UT, which agree with each other very well. The small difference in the J_{sc} and FF is because UT's simulator is slightly insufficient in the red, leading to a lower FF and a higher J_{sc} for a triple cell limited in the current by the top cell. The total-area η measured by NREL for GD585-3#33 is 11.8% (12.55% active-area), as shown in Figure 3.

We have conducted light soaking stability tests for these UT fabricated triple-junction solar cells. After 1000 hours of one-sun light soaking at 50 ^{o}C, these triple cells degrade around 11-12% and show stable active-area efficiency above 10.5% with the highest stable efficiency (active area) at 10.7%, shown in Figure 4. The achievement of 10.7% stable efficiency is a significant improvement from our previously fabricated triple junction solar cells.

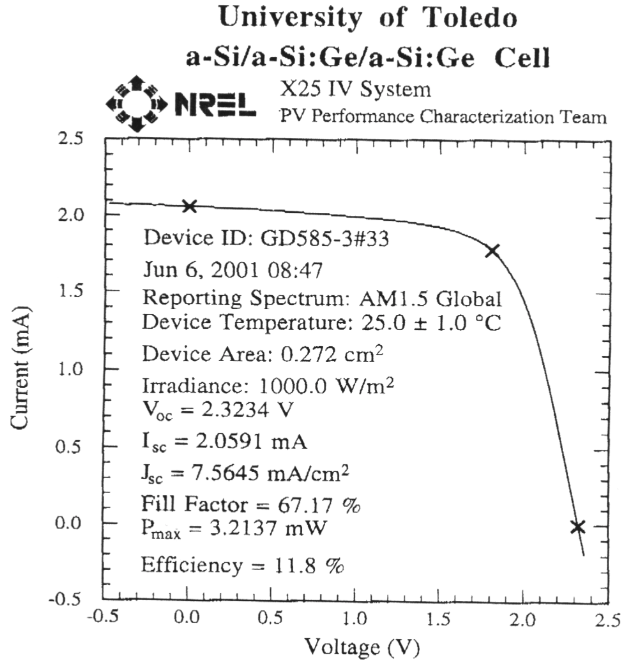

Figure 3 IV curve of GD585 measured at NREL, showing 11.8% initial, total-area efficiency.

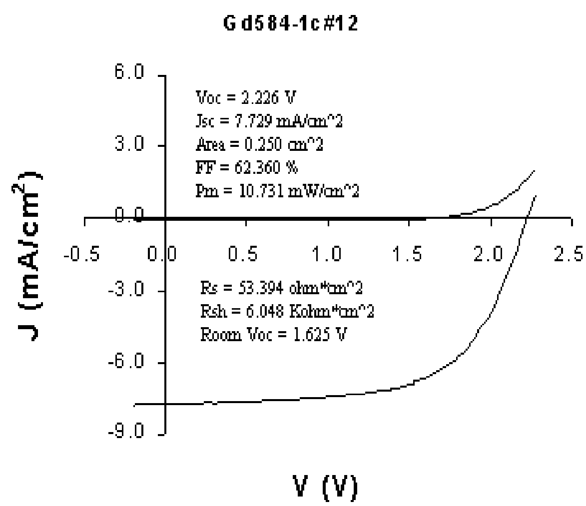

Figure 4. I-V curve of a triple cell showing 10.7% stable efficiency.

SUMMARY

The effect of heavily doped p^+/n^+ interface layers at the tunnel junction of triple-junction solar cells are studied. Preliminary results show that heavily doped thin interface layers could enhance the J_{sc} and FF of the triple cell. However, thicker interface layers (~4 nm or thicker) could result in significant reduction in Voc, Jsc and FF, possibly due to the formation of reversed electrical field at the tunnel junction and electrical potential barriers inside the doped layers.

Incorporating improved component cells and tunnel junctions into triple cell fabrication, we achieved triple-junction a-Si/a-SiGe/a-SiGe solar cells with 12.7% initial active-area efficiency. NREL measurements for these cells show 11.8% initial total-area efficiency (12.55% active-area efficiency). After 1000 hours of light soaking, these triple cells stabilized at efficiencies of 10.5-10.7%, with a degradation of 11-12%.

ACKNOWLEDGMENTS

We would like to thank researchers at ECD, United Solar, NREL and UT CdTe group for collaborations and assistance. Work supported by NREL Thin Film Partnership Program ZAF-8-17619-14 and NDJ-2-30630-08.

REFERENCES

1. J. Yang, A. Banerjee, and S. Guha, Appl. Phys. Lett. 70 2975 (1997).

2. A. Banerjee, J. Yang, T. Glatfelter, K. Hoffman and S. Guha, Appl. Phys. Lett. 64, 1517 (1994).

3. X. Deng, NREL Phase I Annual Subcontract Report, NREL/TP-411-20687, pp65-74. Available NTIS: Order No. DE9696000530 (Feb. 1996).

4. X.Deng, AIP Conf. Proc. 462, NCPV Photovoltaics Program Review, p.297 (1998).

5. X.B. Liao, J. Walker, and X. Deng, MRS Symp. Proc. **557**, 779 (1999).

6. X.B. Liao, W. Wang, and X. Deng, this Proceeding.

Table 1 I-V performance of triple cell having heavily doped tunnel-junction interface layers with different thicknesses

p^+ and n^+ interface layer deposition time (s)		Voc (V)	Jsc (mA/cm^2)	FF (%)	η (%)	Device Number
p_1^+ & p_2^+	n_2^+ & n_3^+					
0	0	2.300	7.25	68.4	11.4	GD846
10	10	2.314	7.54	69.2	12.1	GD840
20	20	2.276	7.55	69.7	11.9	GD842
40	40	2.222	7.02	66.3	10.4	GD854

Table 2 IV performance of top, middle and bottom component cells before and after 1000 hours of light soaking with 1 sun intensity at 50 °C.

Cell Number	Cell Type	Subs		Voc (V)	Jsc (mA/cm^2)	FF (%)	η (%)	Degradation (%)
Gd550-1	Top	SS	Initial	1.00	9.49	71.61	6.77	
			Stable	0.98	9.20	66.66	6.01	11.23
Gd572-2	Middle	BR	Initial	0.80	18.95	65.51	9.97	
			Stable	0.78	19.63	54.14	8.29	16.85
Gd575-2	Bottom	BR	Initial	0.62	22.85	60.96	8.57	
			Stable	0.62	22.94	52.44	7.41	13.54

Table 3 IV performance for triple-junction a-Si based solar cells measured at UT and NREL.

Cell#	V_{oc} (V)	I_{sc} (mA)	FF (%)	Active area (cm^2)	Active-area η (%)	Total area (cm^2)	Total-area η (%)	Measurem't Lab
UT585-3#33	2.293	2.084	66.50	0.25	12.71			UT
UT585-3#22	2.286	2.046	66.35	0.25	12.41			UT
UT 585-3#33	2.3234	2.0591	67.17	0.256	12.55	0.272	11.81	NREL
UT 585-3#22	2.3191	2.0331	66.14	0.255	12.41	0.271	11.68	NREL