PREPARATION OF TRIPLE-JUNCTION A-Si:H NIP BASED SOLAR CELLS AT DEPOSITION RATES OF 10 Å/s USING A VERY HIGH FREQUENCY TECHNIQUE

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ABSTRACT

In an effort to find an alternative deposition method to the standard low deposition rate 13.56 MHz PECVD technique, the feasibility of using a 70 MHz rf plasma frequency to prepare a-Si:H based i-layer materials at high rates for nip based triple-junction solar cells has been tested. As a prelude to multi-junction cell fabrication, the deposition conditions used to make single-junction a-Si:H and a-SiGe:H cells using this Very High Frequency (VHF) method have been varied to optimize the material quality and the cell efficiencies. It was found that the efficiencies and the light stability for both a-Si:H and a-SiGe:H single-junction cells remain relatively constant as the i-layer deposition rate is varied from 1 to 10 Å/s. Also these stable efficiencies are similar to those for cells made at low deposition rates (1 Å/s) using the standard 13.56 MHz PECVD technique and the same deposition equipment. Using the knowledge obtained in the fabrication of the single-junction devices, a-Si:H/a-SiGe:H/a-SiGe:H triple-junction solar cells have been fabricated with all of the i-layers prepared using the VHF technique and deposition rates near 10 Å/s. Thin doped layers for these devices were prepared using the standard 13.56 MHz rf frequency and deposition rates near 1 Å/s. Pre-light soaked efficiencies of greater than 10% have been obtained for these cells prepared at the high rates. In addition, after 600 hrs. of light soaking under white light conditions, the cell efficiencies degraded by only 10-13%, values similar to the degree of degradation for high efficiency triple-junction cells made by the standard 13.56 MHz method using i-layer deposition rates near 1 Å/s. Thus, use of this VHF method in the production of large area a-Si:H based multi-junction solar modules will allow for higher i-layer deposition rates, higher module throughput and reduced module cost.

INTRODUCTION

The benefit of the a-Si:H-based manufacturing processes over other photovoltaic technologies in terms of low module cost will only be fully achieved when the scale of production is increased significantly over the present rates (5-10 MW/yr.). In order to achieve production above 25MW/yr. in an economically feasible manner, higher deposition rates for the a-Si(Ge):H i-layers over today's 1-3 Å/s rates need to be achieved. Extensive attempts to increase these rates using the standard PECVD process with a 13.56 MHz rf frequency signal has led to enhanced powder and polyhydride formation in the plasma and poorer stable cell efficiencies. At present, the outlook for achieving high deposition rates (5-10 Å/s) calls for the development of an alternative thin film deposition technique.

Of the alternative high deposition techniques tested, the Very High Frequency (VHF) PECVD technique is presently one of the most promising. Several research groups [1-4] have reported higher efficiencies for cells made using frequencies of 70-100 MHz at i-layer deposition rates between 5 and 10 Å/s than for those prepared at the same rates using the rf deposition technique. Also, Chatham et. al. [1] and Shah et. al.[2] found that the deposition rate of a-Si:H films could be increased to 10-15 Å/s without an observable deterioration in the film properties.

In order to incorporate a new high deposition rate technique into ECD's roll-to-roll manufacturing process [5], we have chosen to test the feasibility of using the VHF technique to

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prepare small area high efficiency a-Si:H/a-SiGe:H/a-SiGe:H triple-junction solar cells with the ultimate goal of preparing high efficiency large area multi-junction solar modules. The VHF technique is desirable because of the ability to apply the technique to ECD's roll-to-roll process with relatively little hardware changes. Here, we discuss the results from the feasibility study for cells prepared in R&D size deposition systems using high i-layer deposition rates. In this study, we have focused on preparing cells with i-layer deposition rates near 10 Å/s in order attempt to achieve an order of magnitude increase in the deposition rate over the state-of-the-art cells.

EXPERIMENT

The a-Si:H nip/a-SiGe:H nip/a-SiGe:H nip triple-junction solar cell structures were fabricated using a research scale, multi-chamber load locked deposition system. Stainless steel substrates coated with current enhancing Ag/ZnO back reflectors were used as the substrates for preparation of the semiconductor structures. The Ag/ZnO back reflectors were prepared in a roll-to-roll manufacturing machine using a DC sputtering technique. Both the thin doped layers and the thin a-Si:H buffer layers, grown between the VHF deposited a-SiGe:H i-layers and the doped layers, were prepared using the conventional PECVD process in which a 13.56 MHz rf signal is used. To fabricate the a-Si:H and a-SiGe:H i-layers, a fixed VHF frequency of 70 MHz was used. To improve the cell properties, buffer layer and i-layer deposition conditions were altered including substrate temperature, hydrogen dilution, active gas flows, chamber pressure and applied power.

After fabrication of the triple-junction structure, the devices were completed by depositing Indium Tin Oxide (ITO) conductive layers and then Aluminum collection grids. Both the ITO and Al layers were prepared using standard evaporation techniques.

To characterize the cells, standard IV and spectral response (quantum efficiency) measurements were made. For optimization of the a-Si:H cells, standard white AM1.5 light was used to obtain the IV data. For optimization of the a-SiGe:H cells for the green-red light absorbing middle and bottom structures, the AM1.5 light for the IV measurements was filtered using a 530 nm cutoff filter to simulate the absorption due to a top a-Si:H cell for the middle cells and a 630 nm cutoff filter for the bottom cells. During optimization of the component cells, top and middle single-junction cells were fabricated without Ag/ZnO back reflectors while the bottom nip cells were. This was done because in the triple-junction structure, the bottom cell reaps almost all of the benefit of the back reflector layers. To complete light soaking studies, the cells were subjected to 600-1000 hrs. of one sun light with the cell temperature fixed at 50°C. The i-layer thicknesses were determined using capacitance techniques.

RESULTS AND DISCUSSION

Prior to discussing results for the triple-junction cells, data for component a-Si:H and a-SiGe:H cells whose i-layers were prepared at deposition rates of 10 Å/s will be reviewed.

a-Si:H and a-SiGe:H Single-Junction Cells

We have earlier reported results for a-Si:H nip single-junction cells whose i-layers were prepared using the VHF technique at 10 Å/s. The general conclusion from these studies was that by using the VHF technique and careful selection of deposition conditions, the initial and stable cell efficiencies could be made to remain relatively constant with varying i-layer deposition rate up to 10 Å/s for cells prepared without current enhancing Ag/ZnO back reflectors [3]. The cells had i-layer thicknesses near 2300 Å, short circuit currents (J_{sc}) values near 10 mA/cm^2 and stable cell efficiencies near 5.5%. Similar efficiencies were obtained for cells of similar thickness prepared in the same deposition system using the standard rf PECVD technique with a 13.56 MHz frequency and i-layer deposition rates near 1 Å/s. For a-Si:H cells with Ag/ZnO back reflectors, average initial cell efficiencies of 10.3% have been achieved with these cells with i-layer thicknesses of 3000 Å. An IV curve for such a cell is shown in Figure 1. After 100 hrs. of light soaking in white light, these cell efficiencies degrade by 20%, typical degradation percentages for cells of a similar i-layer thickness prepared by the standard rf PECVD technique at i-layer deposition rates of 1 Å/s.

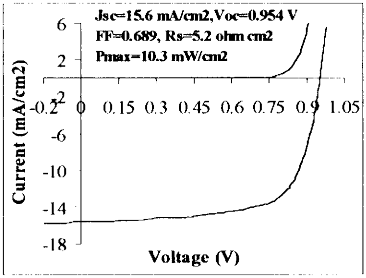

Figure 1. IV plot for a-Si:H cell whose i-layer was prepared at 10 Å/s using VHF technique.

Table I compares data for a-SiGe:H cells prepared with the same deposition equipment using the VHF technique with those made using the standard 13.56 MHz. These cells were also prepared during the same period of time. To judge the potential use of the VHF technique as a method to prepare middle and/or bottom cells for triple-junction structures, we compare in the table IV data obtained using 530 nm filtered AM1.5 light. Again, the 530 nm filter eliminates light typically absorbed by the a-Si:H top cell. Comparing cells with similar J_{sc} values and i-layer thickness, a-SiGe:H cells made by the VHF technique also have similar initial efficiencies to those prepared in the same deposition system using the 13.56 MHz.

The high rate VHF produced a-SiGe:H cells and low rate 13.56MHz produced cells also have similar efficiencies after light soaking as can be seen from the data in Table 2. Cells with similar J_{sc} values have similar stable efficiencies. Some interesting results are the properties for the cell made by the VHF method at a rate of 2 Å/s. The stable efficiencies and FF are actually higher for devices made under these conditions than those made by the 13.56 MHz method at low rates. We have recently improved the efficiencies for the VHF prepared cells and are now achieving higher efficiencies for the a-SiGe:H devices. IV plots for these improved cells prior to light soaking are shown in Figures 2 and 3. Again these data were obtained using AM1.5 light filtered with the 530nm low-bandpass filter.

Table 1.

Data for VHF a-SiGe:H cells prior to light soaking.

Freq. (MHz)	Dep. Rate (Å/s)	i-layer thickness (Å)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	R_s (Ωcm^2)	Initial P_{max} (mW/cm^2)
13.56	0.95	2400	8.50	0.751	0.552	12.3	3.51
13.56	0.92	2100	7.93	0.752	0.575	11.8	3.42
13.56	6.1	2260	7.43	0.711	0.550	14.4	2.91
70	9.5	2000	8.07	0.760	0.579	10.7	3.55
70	10.2	2150	8.15	0.750	0.571	12.1	3.49

Table 2.
Data for a-SiGe:H cells after light soaking for 600 hrs. under white light conditions.

Freq. (MHz)	Dep.Rate (Å/s)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	P_{max} (mW/cm^2)
13.56	0.5	6.93	0.703	0.517	2.52
13.56	0.5	7.02	0.704	0.510	2.52
13.56	0.79	6.97	0.703	0.518	2.54
70	2.0	7.06	0.699	0.543	2.68
70	10.0	7.08	0.675	0.527	2.52
70	9.3	6.92	0.686	0.521	2.47

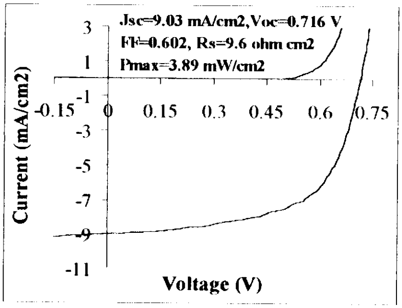

Figure 2. IV curve for a-SiGe:H cell made using VHF technique.

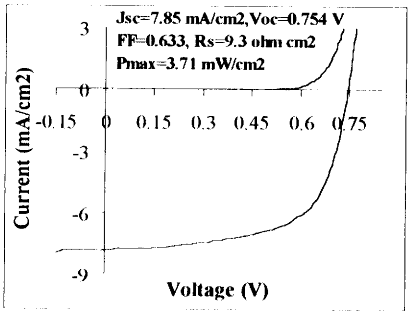

Figure 3. IV curve for a-SiGe:H cell made using VHF technique.

a-Si:H/a-SiGe:H/a-SiGe:H Triple-Junction Cells

Using the optimized conditions obtained from the fabrication of the single-junction structures, a-Si:H/a-SiGe:H/a-SiGe:H triple-junction solar cell devices have been fabricated using the VHF technique to deposit all of the i-layers at rates near 10 Å/s while the doped layers were prepared using the 13.56 MHz technique at rates near 1 Å/s. Using this method, devices with initial active area efficiencies between 9.5 and 10% and total area efficiencies between 9.0 and 9.5% were made. A selection of these cells were light soaked for 600 hrs. under white light conditions and the efficiencies were found to degrade by 10-13%.

However, the uniformity of the depositions across the substrate platform with the optimized conditions initially limited our ability to achieve higher efficiencies for the triple-junction structures. Specifically, under the optimized conditions, there were sharp gradients in thickness, deposition rate and Ge content across the 4" x 4" substrate area. Figure 4 displays the variation in deposition rates across the substrate for the a-Si:H i-layer. The rate was highest near the Gas Inlet, tapering off to the lowest values at the Gas Outlet. This variation in rate was not due to gas depletion since the non-uniform deposits persisted even at very high gas flows. The variations in i-layer thickness and deposition rate led to variations in the J_{sc} and FF across the substrate. The variations in Ge content led to gradients in the V_{oc} across the platform as is shown in Figure 5 for and a-SiGe:H bottom cell. For the triple-junction structure, the variation in i-layer thickness and bandgap made optimization of the current matching between the three component cells difficult.

Gas Inlet

10.8		11.9	11.9		11.6		10.0
10.7	11.3	11.4	11.2	11.1	11.1	10.7	9.8
10.0	10.3	10.4	10.3		10.0	9.7	
8.7				9.1	8.9	8.7	8.1
7.5	8.0	8.2	8.2	8.1			
	7.7	7.9		7.8	7.7		6.9
	7.5	7.7		7.6	7.6	7.3	6.8
6.9				7.2	6.7	7.0	6.5

Gas Outlet (Pump Out)

Figure 4. Deposition rate across substrate platform for a-Si:H cell.

Gas Inlet

		525	508		518	548	581
590		536	522		527	548	581
607		563	553	549		570	596
		590		586	588	597	
661	647	639	636	649			
671	658	652	647	657	657		681
678	669			665		676	687
691	681	678	677	679	684	689	697

Gas Outlet (Pump Out)

Figure 5. V_{oc} (mV) across substrate platform for a-SiGe:H cell.

In order to improve the uniformity, a wide range of parameter space was scanned to study each of the parameter's effect on the deposition profile across the substrate. Variation of the chamber pressure was found to have the greatest effect on the deposition profile. Only at very low pressures was it possible to obtain not only uniform profiles but also deposition rates near 10 Å/s. At these low pressures, variation of other deposition parameters was possible to alter the deposition rate and optimize the i-layer quality without altering the deposition profile greatly. Figure 6 displays the uniform deposition rate for the a-Si:H i-layer at the low pressure conditions while Figure 7 shows the improvement in V_{oc} uniformity for the a-SiGe:H bottom cell.

Gas Inlet

11.6	11.6	11.7	11.7	11.4		11.6	11.8
11.7	11.7	11.9	11.9		11.8	11.9	12.1
11.7	11.7	11.8	11.8		11.8	11.9	12.2
11.9		11.7	11.6	11.9	11.5	11.7	12.1
	11.4	11.1	11.2	11.1			
12.1	11.6	11.3	11.1	11.0	11.3	11.5	12.0
					11.2	11.5	12.1
12.0			11.2	10.8		11.4	12.0

Gas Outlet (Pump Out)

Figure 6. Deposition rate across substrate platform for a-Si:H cell.

Gas Inlet

659	661		660				657
653	655	656					646
			647		645		638
	642	643		640	636		628
625	630			640			
622	625	626			632		629
						627	628
	624						627

Gas Outlet (Pump Out)

Figure 7. V_{oc} (mV) across substrate platform for a-SiGe:H cell.

Incorporating the new deposition conditions that gave more uniform film deposits led to the achievement of initial triple-cell active area efficiencies of 10.4 -10.5%. A representative IV curves for such devices are shown in Figures 8 and 9. The current matching for the cells have yet to be fully optimized, thus further improvement in the efficiencies should come with proper matching. While these cells have yet to be sufficiently light soaked, considering the similarity of the i-layer thicknesses for these cells and those of the 9.5-10% cells, it is likely that these cells will degrade by 10-13% after extended light soaking periods. Further optimization of the deposition conditions for these triple-junction devices should lead to higher stable efficiencies.

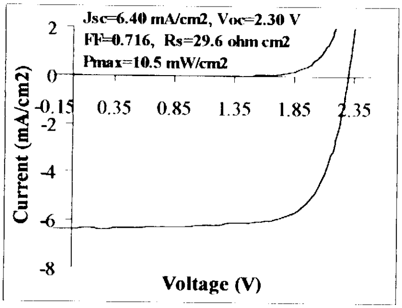

Figure 8. IV curve for triple-junction cell.

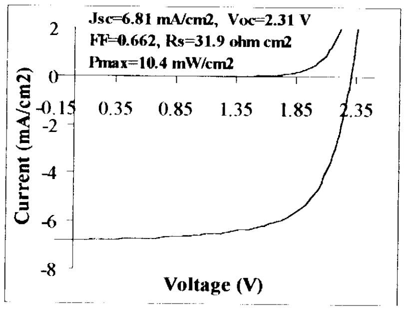

Figure 9. IV curve for triple-junction cell.

DISCUSSION AND CONCLUSIONS

The 10.4 - 10.5% efficiencies obtained for the triple-junction cells are impressive when one considers that 1) all of the i-layers were prepared at deposition rates near 10 Å/s, and 2) that triple-junction cells made in the same deposition system using i-layer deposition rates near 1 Å/s have pre-light soaked efficiencies just above 11%. With further improvement of the current matching of the high rate, VHF produced cells and the baseline efficiencies of our research reactor, higher efficiencies beyond 10.5% should be obtainable.

In terms of the VHF technique for high rate deposition in a large-area production line, proper selection of deposition hardware and the hardware geometry will be critical for obtaining the required deposition uniformity. Without good thin film uniformity, obtaining the current matching needed for high performance modules will not be possible. This does not seem to be an insurmountable problem since some research on cathode hardware for the application of the VHF technology has already been done with some reasonable solutions [6]. Since we have obtained uniform deposits using the VHF technique and low deposition rates (2 Å/s), the non-uniformities we have outlined are primarily due to the high deposition rates we are using. Thus, solutions to this problem should address the general issue of application of high growth rate techniques.

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