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Status of nc-Si:H Solar Cells at United Solar and Roadmap for Manufacturing a-Si:H and nc-Si:H Based Solar Panels

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ABSTRACT

This paper reviews the research and development of hydrogenated nanocrystalline silicon (nc-Si:H) solar cells at United Solar Ovonic LLC. We have been studying nc-Si:H solar cells since 2001 and have made significant progress. We have achieved an initial active-area cell efficiency of 15.1% using an a-Si:H/a-SiGe:H/nc-Si:H triple-junction structure, a stable active-area cell efficiency of 13.3% using an a-Si:H/nc-Si:H/nc-Si:H triple-junction structure, and a stable aperture-area (420 cm^2) fully encapsulated module efficiency of 9.5% using an a-Si:H/nc-Si:H double-junction structure. Although the cell efficiencies with nc-Si:H in the middle and/or bottom cells have exceeded the corresponding efficiencies achieved using a-Si:H and a-SiGe:H, we still need to address several critical issues before using nc-Si:H in photovoltaic manufacturing plants. First, the cell efficiency needs to be improved further to show a clear advantage over the conventional a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cell structure. Second, we need to increase the deposition rate further to make the nc-Si:H based technology more cost effective. Third, we need to develop a machine design to overcome the large-area uniformity issue, especially for very high frequency glow discharge deposition. Fourth, we need to qualify nc-Si:H based solar cell product, especially with respect to long term reliability. We have been addressing these critical issues, and will discuss the roadmap for manufacturing a-Si:H and nc-Si:H based solar panels using the roll-to-roll technology.

INTRODUCTION

Since first reported by the Neuchâtel group in 1994 [1], hydrogenated microcrystalline silicon (μc-Si:H) solar cell has attracted significant attention and has been studied widely. Because μc-Si:H materials contain nanometer-size grains and amorphous tissues, μc-Si:H is now more often called nanocrystalline silicon (nc-Si:H) to align with other nano-technologies. Compared to hydrogenated amorphous silicon (a-Si:H) and silicon germanium alloy (a-SiGe:H) solar cells, nc-Si:H solar cell has two advantages. First, its lower optical bandgap close to the value of crystalline silicon results in a high short-circuit current density (J_{sc}), because of enhanced long wavelength response. Second, optimized nc-Si:H solar cells show very little light-induced degradation. However, the major drawback of nc-Si:H cells is the indirect bandgap in the crystalline phase. The optical absorption coefficient in the short wavelength region is lower than that in a-Si:H and a-SiGe:H. Therefore, a thick nc-Si:H intrinsic layer of over one micrometer is normally needed to achieve high J_{sc}. In order to make nc-Si:H solar cell technology cost-effective for solar panel manufacturing, a high deposition rate is essential. The Neuchâtel group also pioneered the use of very high frequency (VHF) glow discharge to increase the deposition rate of a-Si:H and nc-Si:H [1-3]. The second effective method of increasing the nc-Si:H deposition rate is using high pressure and high power radio frequency (RF) glow discharge in the depletion regime [4, 5]. Lately, these two techniques have been combined for even higher deposition rate up to 20-30 Å/s [6, 7]. With efforts from many laboratories over the world, nc-Si:H solar cell efficiencies have improved significantly in the last several years with nc-Si:H single-junction cell efficiency exceeding 10% [8, 9], multi-junction cell efficiency over 15% [10, 11], and large-area module efficiency ~ 13% [11, 12].

United Solar has been studying a-Si:H and a-SiGe:H based solar cells for many years. A world record stable active-area efficiency of 13% was achieved with an a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structure in 1997 [13] followed by a stable aperture-area module efficiency of 10.5% using the same structure in 1998 [14]. This triple-junction spectrum-splitting technology has been successfully transferred to mass production with a significant expansion in manufacturing capacity. We have continued to improve the current technology by optimizing the a-Si:H and a-SiGe:H quality and increasing the deposition rate. At the same time, we started nc-Si:H solar cell research in the summer of 2001 [15-17]. The research strategy is as follows: First, we optimize the deposition parameters at a low rate with small-area cells to prove the concept. Second, we investigate various methods to increase the deposition rate for small-area cells to meet the manufacturing requirements. Third, we test large-area cell deposition to ensure uniformity, and fabricate modules to conduct stability and reliability studies. Finally, once the above studies are completed, we shall build a roll-to-roll pilot deposition for a pre-manufacturing test. This strategy has been proved to be an effective approach for transferring new technology from research laboratory to mass production lines. In this paper, we review our progress in the nc-Si:H solar cell research along this line and compare with the current a-Si:H/a-SiGe:H/a-SiGe:H triple-junction technology, discuss the technical barriers to be overcome before transferring the nc-Si:H solar cell technology to mass production lines, and propose a roadmap for using nc-Si:H based technology in solar panel manufacturing with a high module efficiency at a low cost.

EXPERIMENTAL APPROACHES

Our major work has been focused on small-area nc-Si:H material and device optimizations with a limited effort on large-area module fabrication. The substrates are normally 5-mil-thick stainless steels coated with textured Ag/ZnO or Al/ZnO back reflector. The intrinsic nc-Si:H layer is deposited using various glow discharge techniques including conventional RF, high pressure/high power RF, modified VHF (MVHF), and microwave [16, 17] For small-area cells, indium-tin-oxide (ITO) dots with an active-area of 0.25 cm^2 are deposited as the top transparent contact, and metal grids are deposited on top of the ITO dots for current collection. For large-area module fabrication, we used a multi-chamber RF glow discharge batch machine to deposit the doped and intrinsic layers. Other processes of module fabrication are similar to those used in the manufacturing lines, including short/shunt passivation, wiring, and encapsulation. The small-area cells are characterized using the current density versus voltage (J-V) measurement under a solar simulator with a spectrum close to AM1.5 illumination. Quantum efficiency (QE) measurement is carried out with no optical bias at short circuit for single-junction cells and under appropriate optical and electrical biases for multi-junction cells. J_{sc} is calculated by integration of the QE curve with the AM1.5 spectrum from 300 to 1100 nm. In order to achieve high efficiency, various multi-junction cell structures have been studied, including a-Si:H/nc-Si:H double-junction, and a-Si:H/a-SiGe:H/nc-Si:H and a-Si:H/nc-Si:H/nc-Si:H triple-junction structures. Light soaking experiments are carried out under various light illumination conditions with different electrical biases.

STATUS OF nc-Si:H BASED SOLAR CELLS

Optimization of nc-Si:H single-junction cells and control of nanocrystalline evolution

In the early stage of our nc-Si:H research, we experienced and solved many issues. The first problem was an ambient degradation observed in nc-Si:H solar cells without intentional light soaking, which was caused by high porosity in the material. [15]. The porous structure of some unoptimized nc-Si:H allowed impurity diffusion into the material and degraded the cell performance. In some cases, the ambient degradation was very severe even in an a-Si:H/nc-Si:H double-junction cell; the porous structure of the nc-Si:H caused micro-cracks of the a-Si:H top cell as evidenced by the ambient degradation in the a-Si:H/nc-Si:H double-junction cells [15]. We investigated the deposition parameters and successfully reduced the porosity in the nc-Si:H and improved the cell performance.

The second problem concerns nanocrystalline evolution. It has been reported that nc-Si:H materials made under the conditions close to the nanocrystalline to amorphous transition have a compact structure and the corresponding solar cells showed high efficiencies [18]. This phenomenon implies that the nc-Si:H with a high crystalline volume fraction normally contains a high defect density, presumably resulting from poor grain boundary passivation and post-oxidation through the porous structure. The crystalline volume fraction increases with the nc-Si:H thickness [19]. An example is given in Fig. 1, where the plot on the left is a Raman spectrum from a nc-Si:H solar cell and the one on the right is the crystalline volume fraction estimated from decomposition of the Raman spectra for cells with different intrinsic layer thicknesses [20]. It clearly shows that the crystalline volume fraction increases with the film thickness. It is logical to expect that an increase in the nc-Si:H intrinsic layer thickness would result in an increase in J_{sc}. However, we found experimentally that under certain conditions, J_{sc} reaches a maximum value; further increasing the intrinsic layer thickness does not lead to an increase in J_{sc} [20]. The loss of J_{sc} in the thicker nc-Si:H cells mainly resulted from the reduction in the long wavelength response. Because this loss could be recovered by a reverse bias during the QE measurement, we concluded that the lower J_{sc} in the thicker nc-Si:H cells was not from insufficient absorption, but from poor collection. The collection problem is normally related to

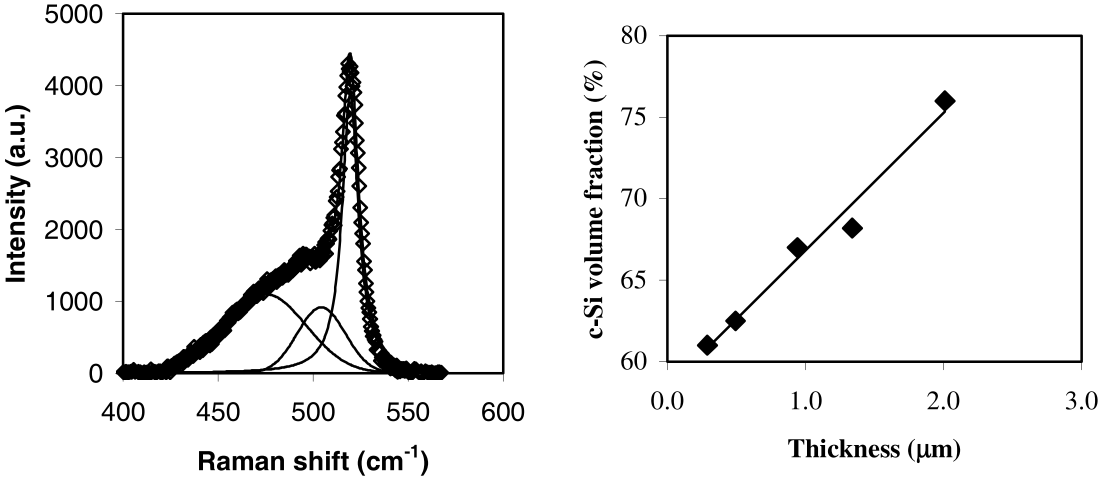

Figure 1. (left) Raman spectrum of a nc-Si:H solar cell with three components of the decomposition and (right) the crystalline volume fraction versus cell thickness.

recombination through defects. The extra thickness caused a high defect density near the *i/p* interface region. Based on a previous study, the *i/p* junction is critical for *n-i-p* (the same for *p-i-n*) solar cells, since more carriers are generated in this region, and the holes have to pass through this region to be collected [21]. The increased defect density could be related to the higher crystalline volume fraction with larger grain sizes, which caused poorer grain boundary passivation. In order to suppress the crystalline evolution, we have developed a hydrogen dilution profiling technique with a continually decreasing hydrogen dilution during the nc-Si:H deposition [20]. A very high hydrogen dilution ratio during the initial deposition reduces the amorphous incubation layer. Dynamically reducing hydrogen dilution during the deposition controls the increase of crystalline volume fraction and grain size. This technique improved the nc-Si:H cell efficiency significantly. Table I lists the J-V characteristics of nc-Si:H single-junction solar cells made with various hydrogen dilution profiles. The baseline cells with an intrinsic layer thickness ~1.2 μm showed an average efficiency of 6.6%, with an average J_{sc} of 21.8 mA/cm^2. Increasing the intrinsic layer thickness did not result in an increase in the J_{sc}, but rather reduced the value. By optimizing the hydrogen dilution profiling, the cell efficiency has been significantly improved, caused by an increase in J_{sc}. Figure 2 shows a comparison of the QE curves of one baseline cell (#14554) with a constant hydrogen dilution ratio, a thicker cell (#14559) with the same constant hydrogen dilution ratio, and two cells with hydrogen dilution profiles (#14578 and #14660). The thicker cell (#14559) did not show a higher long wavelength response, but reduced response in the middle wavelength region, as normally seen in the oxidized cell caused by ambient degradation [15]. The increases of crystalline volume fraction and grain size in the additional thickness are believed to be the origin of the reduced long wavelength response. The hydrogen dilution profiling successfully solved the problem and increased the cell efficiency, especially by enhancing J_{sc} due to the increased middle and long wavelength responses.

Table I. Summary of J-V characteristics of nc-Si:H single-junction solar cells made with various hydrogen dilution profiles. From Profile 1 to Profile 6, the slope of hydrogen dilution ratio versus time was increased.

Sample #	Eff (%)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF			R_s (Ω.cm^2)	Comments
				AM1.5	Blue	Red		
14554	6.74	22.58	0.495	0.603	0.652	0.615	4.4	Baseline
14568	6.48	22.15	0.488	0.599	0.648	0.599	4.0	
14592	6.78	21.32	0.488	0.642	0.690	0.658	3.1	
14594	6.61	20.79	0.486	0.654	0.687	0.648	3.1	
14596	6.61	22.05	0.482	0.622	0.656	0.605	4.0	
14559	6.54	21.48	0.482	0.632	0.678	0.637	4.0	20% thicker than baseline
14562	6.81	21.57	0.484	0.652	0.692	0.651	3.4	
14578	6.63	23.22	0.482	0.594	0.646	0.631	4.3	Profile 1
14580	7.04	22.58	0.484	0.644	0.688	0.662	3.2	Profile 2
14612	7.29	24.41	0.485	0.616	0.659	0.647	3.6	Profile 3
14619	7.81	24.63	0.492	0.645	0.683	0.641	3.4	Profile 4
14642	8.01	23.42	0.502	0.681	0.706	0.700	2.7	Profile 5
14660	8.37	25.15	0.502	0.663	0.679	0.693	3.1	Profile 6

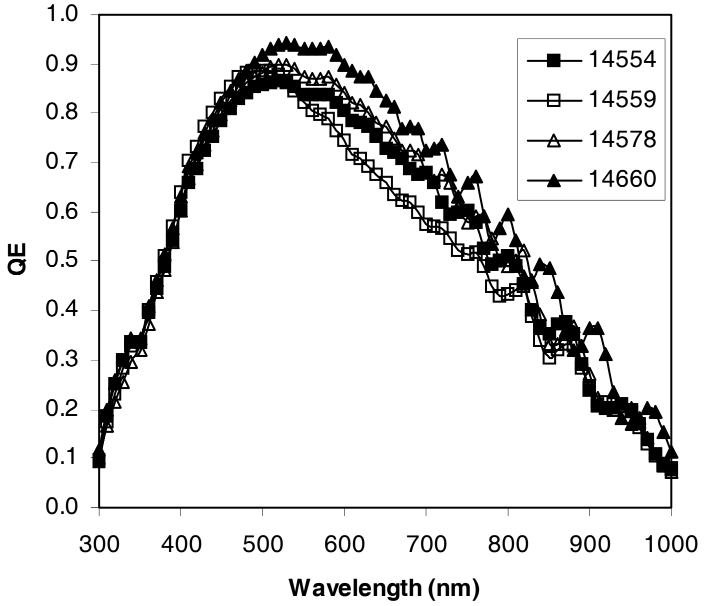

Figure 2. Quantum efficiency of nc-Si:H single-junction cells with various hydrogen dilution profiles. The sample number and the corresponding hydrogen dilution profiles are listed in Table I.

The hydrogen dilution profiling technique was initially developed during the optimization of nc-Si:H solar cells using RF glow discharge at a low rate of ~ 1 Å/s. Since the principle is the same for different deposition techniques at different rates, we applied the same technique to the MVHF deposition and increased the high rate nc-Si:H cell efficiency significantly. Combined with other optimization procedures described in our previous work [16,17], such as properly designed *n/i* and *i/p* buffer layers and optimized light trapping from the textured substrates, we have achieved an initial active-area efficiency of 9% as shown in Fig. 3 [10]. Although this cell has the highest efficiency, the J_{sc} is not sufficient for use as a bottom cell in triple-junction structures. We need to develop deposition parameters to obtain high J_{sc}, especially with an improved long wavelength response. We have optimized the deposition parameters further and obtained a nc-Si:H cell with a J_{sc} close to 27 mA/cm^2 (26.94 mA/cm^2), V_{oc}=0.538 V, and

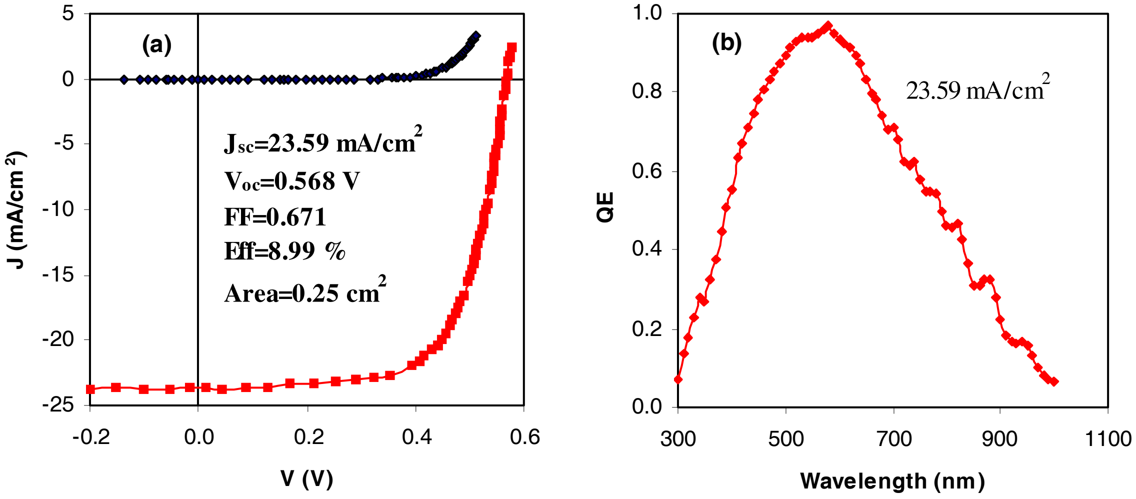

Figure 3. (a) J-V characteristics and (b) quantum efficiency of the best nc-Si:H solar cell, which is suitable for the middle cell in a-Si:H/nc-Si:H/nc-Si:H triple-junction structures.

FF=0.608 for an efficiency of 8.81%.

We have also carried out metastability studies of nc-Si:H solar cells under various illumination and electrical bias conditions [22-25]. We found that nc-Si:H solar cells showed many intriguing metastability behaviors. The light-induced degradation has a range from zero to 15%, depending on the material quality and cell structure. A spectrum dependent light-soaking study found that no light-induced degradation was observed under red light illumination [22], which not only confirms that the light-induced defect generation occurred mainly in the amorphous and grain boundary regions, but also ensures that a nc-Si:H cell will not degrade after prolonged light soaking when it is used as the bottom cell in multi-junction structures. In addition, an enhanced light-induced degradation was observed in nc-Si:H cells under reverse bias during light soaking [23, 24], which is opposite to the situation of a-Si:H solar cells. We also found that an optimized hydrogen dilution profile not only improves the cell efficiency but also the stability against prolonged light soaking [25]. The optimized nc-Si:H single-junction solar cells show an average of ~5% light-induced degradation. The degradation is mainly in J_{sc}, resulting from the reduction of short wavelength response. In practice, nc-Si:H cells are mainly used as the bottom cell (or middle cell) in multi-junction structures, where the short wavelength light does not reach the nc-Si:H bottom cell, and therefore very little light-induced degradation is expected in the nc-Si:H bottom cell.

High Efficiency Multi-Junction Solar Cells with nc-Si:H in the Bottom Cell

We used the optimized component cells to fabricate triple-junction cells. Table II lists the J-V characteristics of several a-Si:H/a-SiGe:H/nc-Si:H cells in the initial and stable states, where the stable state was reached by light soaking under ~100 mW/cm^2 white light at 50 ºC for over 1000 hours. The highest initial active-area efficiency of 15.1% is achieved with the initial J-V characteristics and QE shown in Fig. 4 [10]. After light soaking, a stable efficiency of 13.0% is obtained. From the data in Table II, one can see that the bottom cell current did not degrade after light soaking. Therefore, a bottom cell limited current mismatch resulted in a degradation of only 9.0% (#15506-34). However, the cell with the highest initial efficiency degraded by 17.1%, a large reduction of FF for a middle cell limited current mismatch condition.

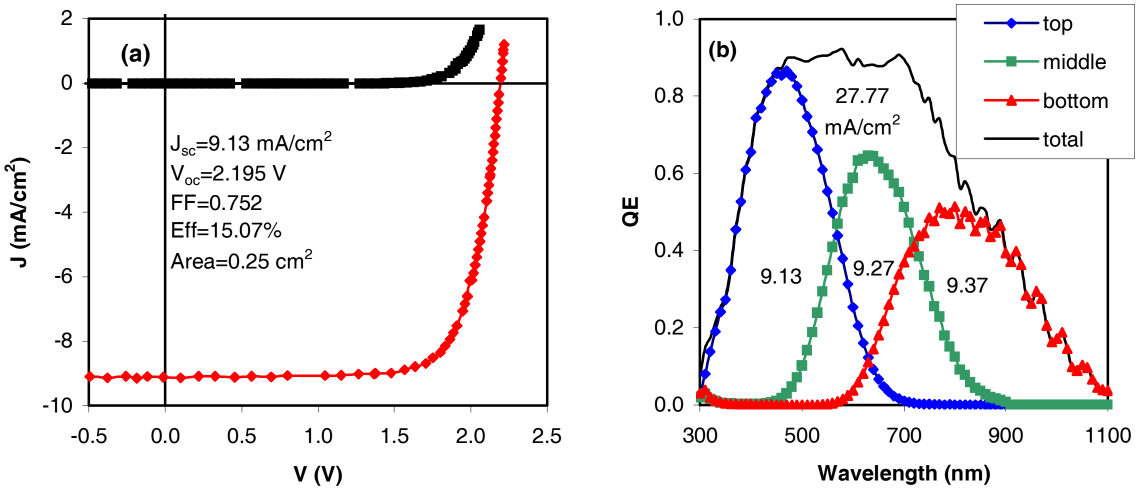

Figure 4. (a) J-V characteristics and (b) quantum efficiency of an a-Si:H/a-SiGe:H/nc-Si:H triple-junction solar cell.

Table II. J-V characteristics of high efficiency a-Si:H/a-SiGe:H/nc-Si:H triple-junction solar cells. Deg. denotes the percentage of light-induced degradation. The bold numbers are the highest efficiencies and italic numbers are the limited current densities for J_{sc}.

Sample	State	Eff (%)	J_{sc} (mA/cm^2)	QE (mA/cm^2)			V_{oc} (V)	FF
				top	middle	bottom		
15501-34	Initial	14.77	9.11	*9.11*	9.24	9.20	2.145	0.756
	Stable	12.62	8.69	8.85	*8.69*	9.12	2.101	0.691
	Deg.	14.6%	4.6%	2.9%	6.0%	0.9%	2.1%	8.6%
15506-33	Initial	**15.07**	9.13	*9.13*	9.27	9.31	2.195	0.752
	Stable	12.49	8.63	8.74	*8.63*	9.24	2.116	0.684
	Deg.	17.1%	5.5%	4.3%	6.9%	0.8%	3.6%	9.0%
15506-34	Initial	14.27	8.74	9.25	9.41	*8.74*	2.167	0.755
	Stable	**12.98**	8.74	8.97	8.88	*8.74*	2.110	0.704
	Deg.	9.0%	0	3.0%	5.6%	0	2.6%	6.7%

Table III summarizes the J-V characteristics of several a-Si:H/nc-Si:H/nc-Si:H triple-junction solar cells in the initial and light-soaked states. The highest initial active-area efficiency of 14.1% was achieved [10,25]. Although the a-Si:H/nc-Si:H/nc-Si:H triple-junction structure did not have the highest initial efficiency, it showed a very small light-induced degradation of 4.3%, resulting from a better stability of the nc-Si:H middle cell than that of the a-SiGe:H middle cell. A stable active-area efficiency of 13.3% is achieved with this cell structure, which exceeds the stable active-area efficiency achieved using the conventional a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structure [13].

Table III. J-V characteristics of high efficiency a-Si:H/nc-Si:H/nc-Si:H triple-junction solar cells. Deg. denotes the percentage of light-induced degradation. The bold numbers are the highest efficiencies and italic numbers are the limited current densities for J_{sc}.

Sample	State	Eff (%)	J_{sc} (mA/cm^2)	QE (mA/cm^2)			V_{oc} (V)	FF
				top	middle	bottom		
13955-33	Initial	**14.14**	9.11	9.11	9.72	*9.11*	1.965	0.790
	Stable	13.19	8.79	*8.79*	9.56	9.04	1.947	0.771
	Deg.	6.7%	3.5%	3.5%	1.6%	0.8%	0.9%	2.4%
13955-24	Initial	13.86	8.89	9.02	9.52	*8.89*	1.981	0.787
	Stable	**13.26**	8.72	8.75	9.25	*8.72*	1.973	0.771
	Deg.	4.3%	1.9%	3.0%	2.8%	1.9%	0.4%	2.0%
14005-33	Initial	13.67	8.99	9.44	9.54	*8.99*	1.944	0.782
	Stable	13.24	8.92	9.04	9.42	*8.92*	1.933	0.768
	Deg.	3.1%	0.8%	4.2%	1.3%	0.8%	0.6%	1.8%

Large-Area a-Si:H/nc-Si:H Double-Junction Solar Cells

The next step towards the manufacturing of nc-Si:H based solar panels is to test the feasibility of making large-area modules [26]. We used an a-Si:H/nc-Si:H double-junction structure on Ag/ZnO BR to prove the concept, because it is easier to make than triple-junction cells. We used a large-area multi-chamber RF glow discharge system, which can hold a 14×15 in^2 substrate. The deposition time of the nc-Si:H intrinsic layer was 50 minutes at a deposition

Table IV. Initial and stable performance of a-Si:H/nc-Si:H double-junction mini-modules with an aperture area of 45 cm^2.

Sample #	State	Temp (°C)	V_{oc} (V)	FF	J_{sc} (mA/cm^2)	P_{max} (W)	Eff (%)	Eff_{corr} (%)
10490F2	Initial	26.6	1.425	0.741	11.40	0.542	12.03	12.07
	Stable	25.4	1.403	0.688	11.25	0.489	10.86	10.87
10500F1	Initial	26.6	1.430	0.738	11.46	0.544	12.08	12.12
	Stable	25.6	1.409	0.665	11.43	0.482	10.71	10.72
10500F2	Initial	26.9	1.432	0.736	11.64	0.552	12.26	12.31
	Stable	25.6	1.406	0.682	11.44	0.494	10.97	10.98
10500G3	Initial	26.6	1.441	0.743	11.37	0.548	12.18	12.22
	Stable	25.9	1.419	0.686	11.12	0.487	10.82	10.83

rate ~4-5 Å/s. We first used the small-area (0.25-cm^2 active area) cells to check the uniformity of the cell efficiency distribution over the deposition area. By optimizing the deposition parameters, a reasonable uniformity was established with a standard deviation of 5.2% over an area of 645 cm^2. The highest initial active-area (0.25 cm^2) cell efficiency of 13.6%, with J_{sc}=12.15 mA/cm^2, V_{oc}=1.429 V, and FF=0.783, has been achieved. After light soaking, this cell stabilized at 12.4% with J_{sc}=12.01 mA/cm^2, V_{oc}=1.423 V, and FF=0.726. We made a-Si:H/nc-Si:H modules with different aperture areas. Table IV listed the performance data of mini-modules with an aperture area of 45 cm^2 but without encapsulation. The initial aperture-area efficiency is slightly over 12%, and the average light-induced degradation is about 11%. Table V lists the performance data of a-Si:H/nc-Si:H double-junction modules with an aperture area of ~420 cm^2, where the initial aperture-area efficiency before the encapsulation is about 11.5%. It is smaller than the efficiency of the mini-modules due to the non-uniformity of the deposition. In the final state after encapsulation and light soaking, the efficiency dropped to 9.0%-9.5%,

Table V. Performance of a-Si:H/nc-Si:H double-junction modules with an aperture area of ~420 cm^2, where T is the measurement temperature, Eff the efficiency at T, and Eff_c the corrected efficiency to 25 °C. State A is the as-deposited state before encapsulation, State B is after encapsulation and light soaking under 100 mW/cm^2 of white light at 50 °C for 500 hours. The comment column indicates the measurement site at United Solar (USO) or at NREL.

Serial #	State	Temp (°C)	V_{oc} (V)	FF	J_{sc} (mA/cm^2)	P_{max} (W)	Eff (%)	Eff_c (%)	Comment
10534 (01)	A	26.1	1.425	0.694	11.49	4.770	11.36	11.38	USO
	B	27.6	1.383	0.624	10.6	3.834	9.13	9.18	
10536 (03)	A	26.4	1.422	0.708	11.31	4.784	11.39	11.42	USO
	B	27.6	1.382	0.624	10.52	3.807	9.07	9.12	
		25.0	**1.455**	**0.642**	**9.68**	**3.816**		**9.13**	**NREL**
10582 (04)	A	25.6	1.440	0.729	11.21	4.943	11.77	11.78	USO
	B	27.8	1.388	0.628	10.50	3.845	9.15	9.22	
10583 (02)	A	25.6	1.435	0.722	11.10	4.829	11.50	11.51	USO
	B	27.6	1.400	0.641	10.38	3.917	9.33	9.38	
		25.0	**1.461**	**0.648**	**9.74**	**3.797**		**9.22**	**NREL**
10587 (05)	A	25.6	1.438	0.689	11.68	4.859	11.57	11.58	USO
	B	27.8	1.400	0.650	10.44	3.987	9.49	9.56	

resulting from ~5-6% encapsulation loss and ~12-14% light-induced degradation. Measurements at NREL gave efficiencies similar to those measured at United Solar, although the individual parameters are different, possibly caused by the difference in the spectra of the solar simulators.

FUTURE WORK AND THE ROADMAP FOR nc-Si:H BASED SOLAR PANEL MANUFACTURING

United Solar has been manufacturing multi-junction solar panels since 1986. From a pilot plant production of about 600 kW in 1986, it has emerged as one of the largest U.S. owned manufacturers of solar panels having a current annual production capacity of 58 MW. Two additional 60 MW plants are under construction in Michigan, USA, and the total annual capacity will reach 180 MW in 2008. Our plan calls for 300 MW annual capacity by 2010. United Solar's evolution of manufacturing capacity and future expansion plan are illustrated in Fig. 5. The spectrum splitting a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cell structure has been used in the two manufacturing plants today and will be used in the two 60 MW plants currently under construction. The question is which cell structure will be chosen for the future plants and whether the a-Si:H and nc-Si:H based technology is ready for manufacturing.

Several companies have been working on a-Si:H and nc-Si:H based thin film solar panel manufacturing [11, 27, 28], demonstrating that the concept has been proven and certain technical barriers have been overcome. The majority of these companies are using the *p-i-n* cell structure on glass superstrate. We make *n-i-p* cells on flexible steel substrates in a roll-to-roll operation. Currently, we still need to address the following critical issues.

The first issue is to achieve higher module efficiency than that in the current product. Figure 6 plots the cell, module, and product efficiencies achieved using the a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structure at various stages. The highest initial and stable active-area efficiency of 15.2% and 13.0% were achieved using a low rate deposition of ~ 1Å/s on Ag/ZnO back reflector [13]. By increasing the deposition rate to 3 Å/s, the efficiencies became 13.0% and 11.3%; respectively. On Al/ZnO back reflectors, the efficiencies further dropped to 11.7% and 9.8%, respectively. The initial and stable aperture-area module efficiencies of 10.5% and 8.9% were achieved at ~3Å/s on Al/ZnO in the research and development group. After transferring this technology to the manufacturing lines, the current products show an average

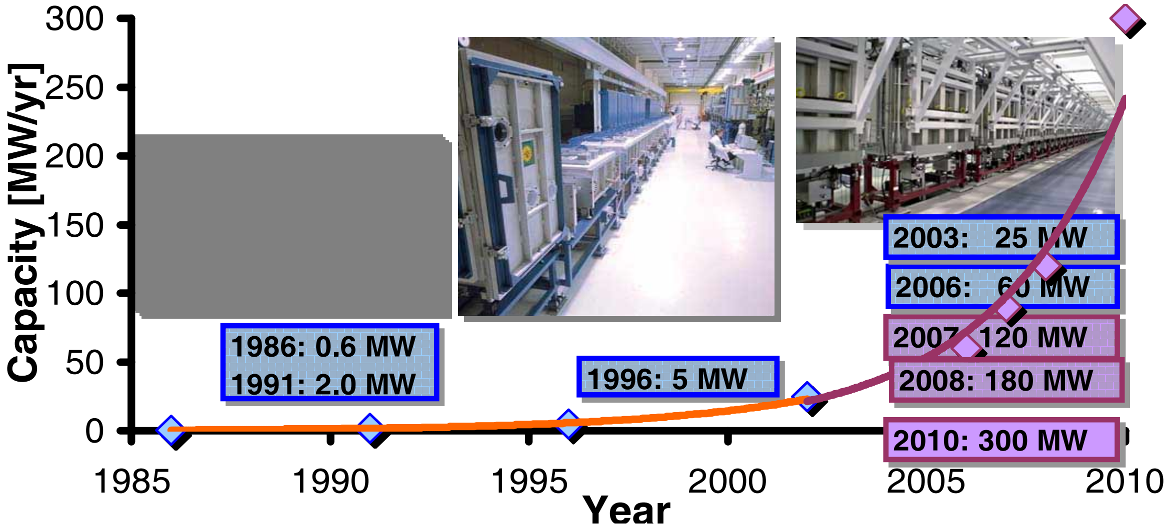

Figure 5. History and future expansion plan of United Solar's manufacturing capacity.

aperture-area efficiency of ~8%. As discussed in the previous section, our major research activities are still focused on the cell level. The champion cell performance with nc-Si:H in the bottom cell is similar to the highest efficiency achieved with the a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structure. In order to make a sound business decision, the new cell structure with nc-Si:H has to show a significant advantage of at least >10% in the cell performance over the conventional structure. Therefore, a higher stable active-area efficiency of over 14% is our near term goal. The most important milestone for nc-Si:H based modules made with a similar total deposition time to the current manufacturing process on Al/ZnO back reflector is a stable aperture-area efficiency of larger than 10%. It is clear that our current status has not reached the efficiency milestone yet.

The second issue is to increase the nc-Si:H deposition rate to a level resulting in equal or shorter total deposition time. Compared to the current manufacturing machine, the deposition rate of nc-Si:H needs to be at least 20 Å/s if an a-Si:H/nc-Si:H/nc-Si:H triple-junction structure is used. Currently, the deposition rate of nc-Si:H intrinsic layer is ~5-8 Å/s. Significant efforts are needed to increase the deposition rate to meet the requirement of equal (or shorter) deposition time compared to the current manufacturing technology.

The third issue is the large-area uniformity and compatibility with the roll-to-roll deposition. At the current stage, VHF has been shown to be a possible deposition method for the intrinsic nc-Si:H deposition. However, the large-area uniformity is a great challenge for the cathode design. In principle, it is achievable by simulating the electromagnetic field distribution for various cathode geometries, such as the ladder structure used by Mitsubishi Heavy Industries, Ltd. [27]. At United Solar, we have not put, as yet, enough effort on large-area VHF cathode design. In addition, the high pressure/high power depleting regime has been used for increasing the deposition rate while maintaining high-quality nc-Si:H. One critical requirement for this regime is a small spacing between the cathode and the substrate. For a very large roll-to-roll machine with flexible substrate, keeping the same uniform spacing is also a great challenge.

The fourth issue is the reliability of the product. United Solar's a-Si:H/a-SiGe:H/a-SiGe:H triple-junction solar panels on Al/ZnO has passed various reliability tests under different harsh conditions. Any new product also must pass all the reliability tests. Currently, we have not carried out such tests. One concern is the adhesion of the solar cells to the substrate, because

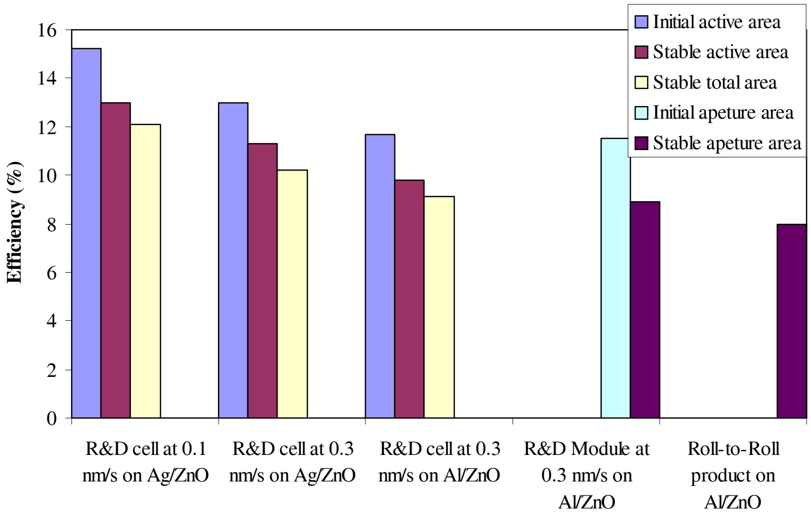

Figure 6. Cell, module, and PV product efficiencies using a-Si:H/a-SiGe:H/a-SiGe:H triple-junction technology.

the nc-Si:H intrinsic layers are much thicker than a-Si:H and a-SiGe:H intrinsic layers in multi-junction solar cells. The internal stress may accumulate with the film thickness, and then the adhesion may become an issue.

The four areas are identified as the major tasks for future research towards the development of a-Si:H and nc-Si:H based solar panel manufacturing technology. We have proposed a roadmap to achieve the goals to U.S. Department of Energy's (DOE) Solar America Initiative (SAI) Program. We shall demonstrate that by integrating a-Si:H and nc-Si:H in a multi-junction structure, an enhancement in stable module efficiencies of >10% can be achieved with the bench mark being the current stable production module efficiency of 8%. In the meantime, we shall increase the nc-Si:H deposition rate to the level such that the total deposition time is similar to the current manufacturing process. We shall design and test various VHF cathodes to achieve large-area uniform nc-Si:H deposition, and evaluate the a-Si:H and nc-Si:H deposition process in a pilot roll-to-roll machine. Finally, we shall conduct reliability testing of the a-Si:H and nc-Si:H based solar panels.

SUMMARY

We have demonstrated that by using nc-Si:H as the bottom cell in triple-junction structures, we can achieve the same initial and stable cell efficiencies as the a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structure. However, there are still major issues that need to be addressed before considering the use of nc-Si:H in solar panel manufacturing plants, namely, increasing the efficiency further; increasing the deposition rate further; improving the large-area uniformity; solving any potential problem associated with the nc-Si:H deposition; and testing the reliability of the a-Si:H and nc-Si:H based panels. We have planned out technical approaches and are ready to resolve these issues under the SAI program.

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REFERENCES

1. J. Meier, R. Flückiger, H. Keppner, and A. Shah, Appl. Phys. Lett. **65, 860** (1994).
2. A. Shah, J. Dutta, N. Wyrsch, K. Prasad, H. Curtins, F. Finger, A. Howling, and Ch. Hollenstein, Mater. Res. Soc. Symp. Proc. **258**, 15 (1992).
3. J. Meier, P. Torres, R. Platz, S. Dubail, U. Kroll, J. A. Anna Selvan, N. Pellaton Vaucher, Ch. Hof, D. Fischer, H. Keppner, A. Shah, K.-D. Ufert, P. Giannoulès, and J. Koehler, Mater. Res. Soc. Symp. Proc. **420**, 3 (1996).
4. L. Guo, M. Kondo, M. Fukawa, K. Saitoh , and A. Matsuda, Jpan. J. Appl. Phys. Part 2 **37**, L1116 (1998).
5. B. Rech, T. Roschek, J. Müller, S. Wieder, and H. Wagner, Technical Digest of 11th PVSEC, Sapporo, Japan, 1999, p. 241.
6. T. Matsui, A. Matsuda, and M. Kondo, Mater. Res. Soc. Symp. Proc. **808**, 557 (2004).
7. Y. Mai, S. Klein, R. Carius, J. Wolff, A. Lambertz, F. Finger, and X. Geng, J. Appl. Phys. **97**, 114913 (2005).

8. Y. Mai, S. Klein, R. Carius, H. Sriebig, X. Geng, and F. Finger, Appl. Phys. Lett. **87**, 073503 (2005).
9. J. K. Rath, A. Verkerk, R. Franken, C. van Bommel, K. van der Werf, A. Gordijn, and R. Schopp, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 1473.
10. B. Yan, G. Yue, J. M. Owens, J. Yang, and S. Guha, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 1477.
11. K. Yamamoto, A. Nakajima, M. Yoshimi, T. Sawada, S. Fukada, T. Suezaki, M. Ichikawa, Y. Koi, M. Goto, T. Meguro, T. Matsuda, T. Sasaki, and Y. Tawada, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 1489.
12. K. Saito, M. Sano, S. Okabe, S. Sugiyama, and K. Ogawa, Solar. Energy Matter & Solar Cells **86**, 565 (2005).
13. J. Yang, A. Banerjee, and S. Guha, Appl. Phys. Lett. **70**, 2975 (1997).
14. A. Banerjee, J. Yang, and S. Guha, Mater. Res. Soc. Symp. Proc. **557**, 743 (1999).
15. B. Yan, K. Lord, J. Yang, S. Guha, J. Smeets, and J-M. Jacquet, Mater. Res. Soc. Symp. Proc. **715**, 629 (2002).
16. B. Yan, G. Yue, J. Yang, A. Banerjee, and S. Guha, Mater. Res. Soc. Symp. Proc. **762,** 309 (2003).
17. B. Yan, G. Yue, J. Yang, K. Lord, A. Banerjee, and S. Guha, Proc. of 3rd World Conference on Photovoltaic Energy Conversion*,* May 11-18, 2003, Osaka, Japan, p. 2773
18. T. Roschek, T. Repmann, J. Müller, B. Rech, and H. Wagner, Proc. of 28th IEEE Photovoltaic Specialists Conference, Anchorage, AK, Sep. 15-22, 2000, (IEEE New York, 2000), p. 150.
19. J. Kočka, A. Jejfar. V. VorlÍček, H. StuchlÍkova, and J. StuchlÍk, Mater. Res. Soc. Symp. Proc. **557,** 483 (1999).
20. B. Yan, G. Yue, J. Yang, S. Guha, D. L. Williamson, D. Han, and C.-S. Jiang, Appl. Phys. Lett. **85**, 1955 (2004).
21. A. Pawlikiewicz and S. Guha, Mater. Res. Soc. Symp. Proc. **118**, 599 (1988).
22. B. Yan, G. Yue, J. M. Owens, J. Yang, and S. Guha, Appl. Phys. Lett. **85**, 1925 (2004).
23. G. Yue, B. Yan, J. Yang, and S. Guha, Appl. Phys. Lett. **86**, 092103 (2005).
24. G. Yue, B. Yan, J. Yang, and S. Guha, J. Appl. Phys. **98**, 074902 (2005).
25. G. Yue, B. Yan, G. Ganguly, J. Yang, S. Guha, C. W. Teplin, and D.L. Williamson, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 1588.
26. G. Ganguly, G. Yue, B. Yan, J. Yang, S. Guha, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 1712.
27. H. Takatsuka, Y. Yamauchi, Y. Takeuchi, M. Fukagawa, S. Goya, and A. Takano, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 2028.
28. T. Repmann, S. Weider, S. Klein, H. Stiebig, and B. Rech, Conf. Record of the 2006 IEEE 4th World Conf. on Photovoltaic Energy Conversion, Hawaii, USA, May 7-12, 2006, p. 1724.