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High Rate Deposition of Amorphous Silicon Based Solar Cells using Modified Very High Frequency Glow Discharge

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ABSTRACT

We report our recent progress on high rate deposition of hydrogenated amorphous silicon (a-Si:H) and silicon germanium (a-SiGe:H) based *nip* solar cells. The intrinsic a-Si:H and a-SiGe:H layers were deposited using modified very high frequency (MVHF) glow discharge. We found that both the initial cell performance and stability of the MVHF a-Si:H single-junction cells are independent of the deposition rate up to 15 Å/s. The average initial and stable active-area cell efficiencies of 10.0% and 8.5%, respectively, were obtained for the cells on textured Ag/ZnO coated stainless steel substrates. a-SiGe:H single-junction cells were also optimized at a rate of ~10 Å/s. The cell performance is similar to those made using conventional radio frequency technique at 3 Å/s. By combining the optimized component cells made at 10 Å/s, an a-Si:H/a-SiGe:H double-junction solar cell with an initial active-area efficiency of 11.7% was achieved.

INTRODUCTION

High rate deposition of thin film solar cells is desirable for increasing throughput and reducing cost of manufacturing solar panels. However, hydrogenated amorphous silicon (a-Si:H) solar cells made using conventional radio frequency (RF) glow discharge at high rates commonly exhibit poor quality [1]. The material contains high density of defects, microvoids, and di-hydride structures, which lead to low initial solar cell efficiencies and poor stability after prolonged light soaking. Therefore, new deposition techniques are needed for increasing the deposition rate without compromising the material quality.

Very high frequency (VHF) glow discharge has been widely used in the deposition of a-Si:H and hydrogenated nanocrystalline silicon (nc-Si:H) materials and devices [2, 3]. Under a similar excitation power density, VHF plasma has a higher ion flux intensity and lower ion energy than the conventional RF plasma, resulting in improved material quality at higher deposition rates [4]. In our laboratory, we used a modified VHF (MVHF) system with an excitation frequency range of 60-75 MHz to make a-Si:H, a-SiGe:H, and nc-Si:H solar cells. An initial efficiency of 11.2% was reported previously in an a-Si:H/a-SiGe:H double-junction solar cell with the a-Si:H intrinsic layer deposited at 8 Å/s and the a-SiGe:H intrinsic layer at 6 Å/s [5]. Recently, we have achieved an initial active-area efficiency of 9.0% for a nc-Si:H single-junction solar cell and a stabilized active-area efficiency of 13.3% for an a-Si:H/nc-Si:H/nc-Si:H triple junction solar cell [6, 7]. In this paper, we report our recent results on high rate deposition of a-Si:H and a-SiGe:H based solar cells. The growth parameters are similar to those used for nc-Si:H cells [6, 7] in the high pressure and high power regime. The initial cell performance and stability as a function of the deposition rate have been systematically studied. The results showed that for a-Si:H single-junction cells made using MVHF, both the initial cell performance and stability are independent of the deposition rate of up to 15 Å/s. This phenomenon is different from a-Si:H cells made using conventional RF glow discharge at high rates [5]. In the RF cells, the cell performance usually decreases and the light-induced degradation increases with increasing deposition rate [1].

We will also present the results of a-SiGe:H single-junction and a-Si:H/a-SiGe:H double junction solar cells made using MVHF technique.

EXPERIMENTAL

A series of a-Si:H *n-i-p* solar cells was made with an MVHF high rate a-Si:H intrinsic layer and RF doped layers. For a given deposition condition, two runs were made: one on specular stainless steel (SS) substrate and the other on Ag/ZnO back reflector (BR) coated SS substrate. The deposition rate of the a-Si:H intrinsic layer was changed from 5 to 15 Å/s by varying the VHF power and the pressure. The thickness of the intrinsic layer was in the range of 200-220 nm. For a-SiGe:H cells, the deposition time of the intrinsic layer was fixed at 4 minutes, which corresponds to a deposition rate of ~10 Å/s. Indium-Tin-Oxide dots with an active-area of 0.25 cm^2 were deposited on the *p* layer as the top contact for current density versus voltage (J-V) and quantum efficiency (QE) measurements. The J-V measurements were conducted under an AM1.5 light at 25 ^oC. The QE measurements were performed under the short-circuit condition at room temperature in the wavelength range from 300 to 1000 nm. The stabilized efficiency of a-Si:H solar cells was reached by light-soaking under the open-circuit condition with 100 mW/cm^2 white light at 50 ^oC for 1000 hours. For a-SiGe:H cells, J-V measurements were also carried out using the same light source with a 530-nm long-pass filter to simulate the condition for a bottom cell in an a-Si:H/a-SiGe:H double-junction structure.

RESULTS AND DISCUSSION

1. a-Si:H single junction cells

The deposition rate of a-Si:H depends on many parameters such as the excitation power density, gas pressure, substrate temperature, and hydrogen dilution ratio. Under a given condition, the most common way to increase the deposition rate is to increase the excitation power. Figure 1 shows the deposition rate of a-Si:H as a function of VHF power. The deposition rate increases continuously in the range of 9-15 Å/s with the VHF power, indicating a non-depleting regime. The deposition rate is also very sensitive to the gas pressure. In the high pressure regime, increasing the pressure leads to a decrease in the deposition rate. In this study, we focused on the range of deposition rate from 5 to 15 Å/s. Table I lists the J-V characteristics of a-Si:H cells on both SS and BR substrates, where the data of short-circuit current density (J_{sc}) are from the integral of the QE curves and the AM1.5 solar spectrum. We used the fill factor (FF) obtained from the measurements under a blue light (FF_b) and a red light FF_b (FF_r) to

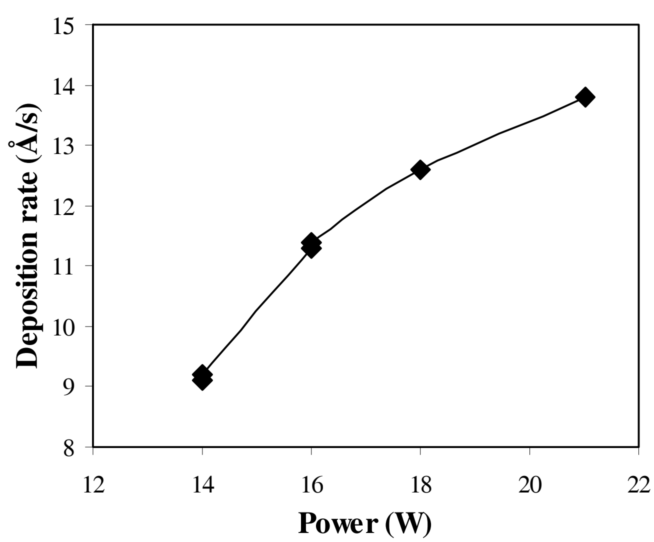

Figure 1. Deposition rate as a function of VHF power.

Table I. J-V characteristics of a-Si:H single-junction solar cells made at different rates on BR and SS substrates. FF_b and FF_r represent the FF measured under low-intensity blue and red lights, respectively. The values of J_{sc} are obtained from the QE measurement.

Sample No.	V_{oc} (V)	FF			J_{sc} (mA/cm^2)	Eff (%)	Substrate	Rate (Å/s)	*i* layer time (s)
		AM1.5	FF_b	FF_r					
14325	0.983	0.712	0.759	0.753	14.34	10.04	BR	5.2	420
14166	1.000	0.735	0.767	0.749	9.71	7.14	SS		
14324	1.001	0.723	0.763	0.750	13.68	9.90	BR	6.1	300
14139	0.974	0.727	0.765	0.780	9.62	6.81	SS		
14347	0.987	0.702	0.722	0.744	14.67	10.16	BR	9.2	240
14336	0.988	0.710	0.760	0.770	10.36	7.27	SS		
14323	0.993	0.709	0.741	0.741	14.69	10.34	BR	9.3	240
14318	0.978	0.697	0.754	0.763	10.48	7.14	SS		
14346	0.986	0.696	0.716	0.742	14.46	9.92	BR	11.4	222
14335	0.995	0.698	0.764	0.747	10.43	7.24	SS		
14338	0.997	0.704	0.743	0.751	13.68	9.60	BR	11.9	180
14330	0.985	0.714	0.755	0.768	9.96	7.00	SS		
14345	0.984	0.697	0.717	0.742	14.20	9.74	BR	12.6	175
14342	0.986	0.713	0.760	0.767	9.89	6.95	SS		
14348	0.982	0.710	0.717	0.743	14.11	9.84	BR	13.8	156
14333	0.995	0.713	0.769	0.763	9.64	6.84	SS		

probe the quality of the material near the *i/p* interface and the bulk of the intrinsic layer, respectively. One can see that the cell performance does not depend strongly on the deposition rate. Most cells show a high FF_r, reflecting high quality of the a-Si:H intrinsic layer. The average efficiency is around 7% for the cells on SS and 10% on BR. Compared to the cells on SS, the open-circuit voltage (V_{oc}) and FF do not change much for the cells on BR. However, the J_{sc} increased by 40% as a result of the light trapping on the textured Ag/ZnO BR. The intrinsic layer thickness was controlled to be in the range of 200-220 nm for each sample. By increasing the intrinsic layer thickness to 330 nm, an initial active-area efficiency of 10.7% (J_{sc}=15.94 mA/cm^2, V_{oc}=0.993 V, and FF=0.674) was obtained for an a-Si:H single-junction cell deposited on a Ag/ZnO BR substrate at 10 Å/s.

Stability experiments were carried out for all of the a-Si:H cells with different deposition rates on SS and BR substrates. The solar cells were light-soaked under 100 mW/cm^2 white light at 50 ^{o}C for 1000 hours. As a reference, two a-Si:H cells made with RF at a low rate of ~1 Å/s on SS and Ag/ZnO BR substrates were light-soaked together with the high rate MVHF cells. Figure 2 shows the initial and stable efficiencies as well as the light-induced degradation rate as a function of the deposition rate. Within the experimental variation, the light-induced degradation of the efficiency is around 15.5±1.5% for all the cells on both BR and SS substrates. It does not show a clear dependence on the deposition rate. The highest stabilized efficiency of 8.64% (J_{sc}=13.92 mA/cm^2, V_{oc}=0.956 V, and FF=0.649) was achieved with an a-Si:H single-junction cell made at 9.3 Å/s on the BR substrate.

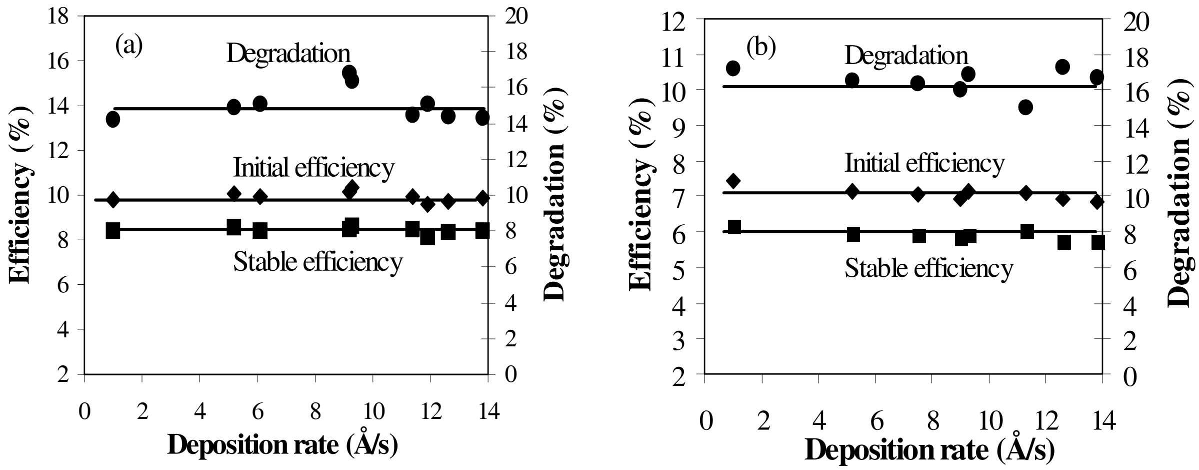

Figure 2. The initial and stable efficiencies and the degradation as a function of deposition rate of a-Si:H solar cells on (a) BR and (b) SS substrates. The cells for 1 Å/s were made by RF.

2. a-SiGe:H single and a-Si:H/a-SiGe:H double junction cells

As mentioned above, both initial performance and stability for the high rate a-Si:H solar cells made by MVHF are independent of the deposition rate of up to 15 Å/s. Encouraged by this result, we then proceeded to optimize high rate a-SiGe:H component cells with the aim of making high efficiency a-Si:H/a-SiGe:H double-junction cells. Usually, high rate a-SiGe:H cell optimization is more difficult than its a-Si:H counterpart. First, compared to the a-Si:H deposition, heavier GeH_3 radicals have a lower mobility on the growing surface, which requires a longer relaxation time to find energetically favorable sites to stay. Second, the Ge-H bond is weaker than the Si-H bond. For a given substrate temperature, the hydrogen content decreases with the Ge/Si ratio, which leads to an insufficient dangling bond passivation thus a high defect density. Increasing the substrate temperature can increase the surface mobility of impinging radicals, but it reduces hydrogen content further and results in a high defect density in the film. Therefore, an optimized temperature is critical for the high rate a-SiGe:H growth. Third, a proper band gap profiling is needed for enhancing the hole collection [8]. In addition, we need to optimize the *n/i* and *i/p* interfaces to reduce the shunt current and interface recombination, and the doped layers to reduce the series resistance and increase V_{oc}. Considering these factors, we chose to optimize a-SiGe:H single-junction cells at a deposition rate of ~10 Å/s, where the deposition time of the a-SiGe:H intrinsic layer was fixed at 4 minutes. Table II lists the J-V characteristics of typical a-SiGe:H cells made at high rate. For comparison, two cells made using RF at deposition rates of 1 Å/s and 3 Å/s are also included. In this study, we focused on intermediate band gap solar cells, which give an AM1.5 open-circuit voltage (V_{oc}) around 0.75 to 0.80 V and is suitable for the bottom cell in an a-Si:H/a-SiGe:H double-junction structure. In order to investigate the long wavelength response and simulate the performance of an a-SiGe:H cell in an a-Si:H/a-SiGe:H double-junction structure, we measured the cell performance under an AM1.5 solar simulator with a 530-nm long-pass filter. From our previous experience, a maximum power density (P_{max}) of 4 mW/cm^2 under the filtered light is a benchmark for good a-SiGe:H component cells on SS substrates. In this study, we achieved an active-area P_{max} of 4.4 mW/cm^2 under an AM1.5 light with the 530-nm long-pass filter. The performance is lower than the cell made by conventional RF glow discharge at 1 Å/s, but comparable to that made at 3 Å/s as shown in Table II. Figure 3 shows the J-V curves and QE spectrum of the optimized a-SiGe:H component cell.

Table II. J-V characteristics of typical a-SiGe:H component cells made using RF and MVHF at different rates. The results in the parentheses were measured under AM1.5 light with a 530 nm long-pass filter.

Sample No.	V_{oc} (V) (> 530 nm)	FF (> 530 nm)	J_{sc} (mA/cm^2) (> 530 nm)	P_{max} (mW/cm^2) (> 530 nm)	Comments
15333	0.763(0.744)	0.690(0.693)	16.48(10.47)	8.68(5.40)	RF 1 Å/s
5183	0.768(0.749)	0.614(0.641)	15.20(9.17)	7.18(4.40)	RF 3 Å/s
14407	0.795(0.775)	0.667(0.696)	13.49(7.82)	7.15(4.22)	MVHF 10 Å/s
14583	0.768(0.751)	0.648(0.671)	14.41(8.66)	7.17(4.36)	MVHF 10 Å/s
14584	0.768(0.750)	0.664(0.681)	14.23(8.60)	7.26(4.39)	MVHF 10 Å /s

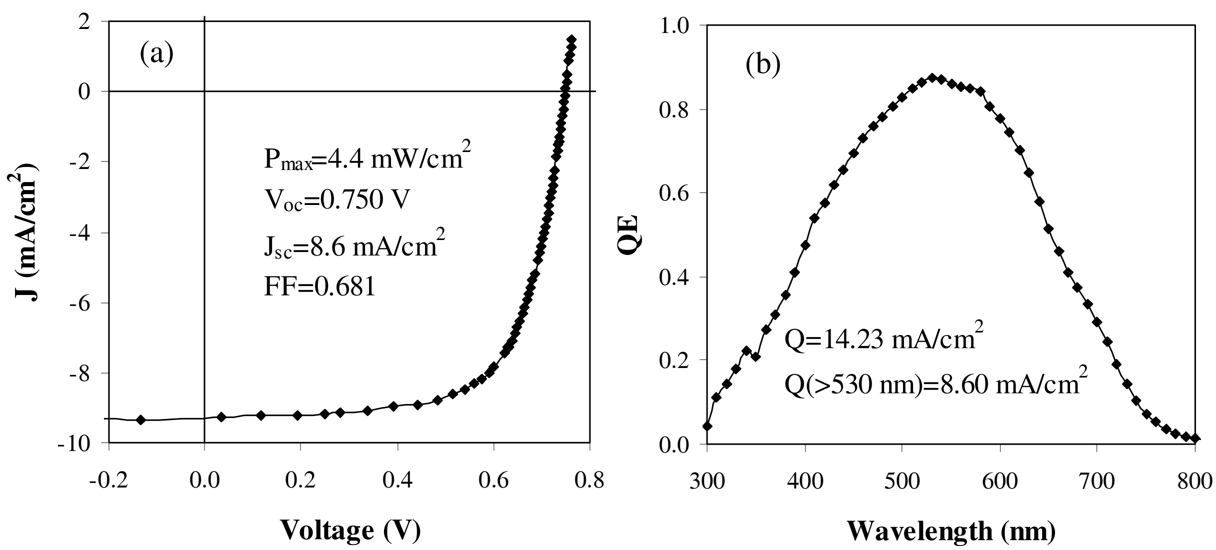

Figure 3. (a) J-V characteristics measured under AM1.5 light with a 530 nm long-pass filter and (b) QE curve of the optimized a-SiGe:H component cell made at 10 Å/s.

Having optimized the a-Si:H top and a-SiGe:H bottom cells, we made a-Si:H/a-SiGe:H double-junction solar cells on Ag/ZnO BR coated SS substrates. The deposition time for both the a-Si:H and a-SiGe:H intrinsic layers was 4 minutes. The J-V characteristics of typical double-junction cells are listed in Table III. An initial active-area efficiency of 11.7% has been achieved. The J-V curves and QE spectrum of the best a-Si:H/a-SiGe:H double-junction cell are plotted in Fig. 4. The light soaking data for the a-SiGe:H single-junction and a-Si:H/a-SiGe:H double-junction cells will be reported when they are available.

Table III. J-V characteristics of the a-Si:H/a-SiGe:H double-junction cells made at high rates. The deposition time of the intrinsic layers for both the top and bottom cells was 4 minutes.

Sample No.	V_{oc} (V)	FF	QE (mA/cm^2) Top	Bottom	Total	P_{max} (mW/cm^2)
14520	1.719	0.717	9.50	10.94	20.44	11.71
14530	1.696	0.664	10.23	10.16	20.39	11.44
14534	1.700	0.679	9.78	10.48	20.26	11.29

CONCLUSION

We have found that the MVHF-deposited a-Si:H solar cells showed good initial efficiency and stability. The most important result is that the cell performance and stability do not depend on the deposition rate of up to 15 Å/s. This is different from the cells made using RF at high rates. The degradation of the RF cells usually increases with the deposition rate. We have also optimized the a-SiGe:H cells at high deposition rates on SS substrates. A P_{max} of 4.4 mW/cm^2 has been achieved for a 0.25 cm^2 cell under the AM1.5 light with a 530-nm long-pass filter, which is comparable to the cells made with RF at 3 Å/s. By combining the optimized component cells, we have achieved an initial active-area efficiency of 11.7% with an a-Si:H/a-SiGe:H double-junction cell on Ag/ZnO coated SS substrates at 10 Å/s.

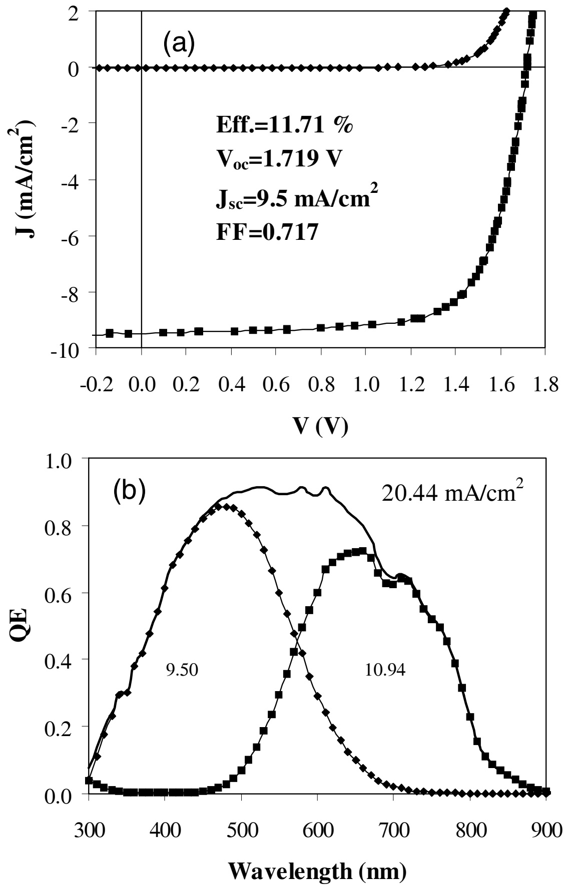

Figure 4. (a) J-V characteristics and (b) QE spectrum of an a-Si:H/a-SiGe:H double-junction cell made at 10 Å/s using MVHF.

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