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Amorphous Silicon and Silicon Germanium Alloy Solar Cells Deposited by VHF at High Rates

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ABSTRACT

A modified very high frequency (MVHF) glow discharge technique is used to deposit amorphous silicon (a-Si) and amorphous silicon-germanium (a-SiGe) alloy solar cells at high deposition rates. High quality a-Si alloy solar cells have been obtained by using MVHF at deposition rates up to ~10 Å/s. The cells show good initial and stabilized efficiencies comparable to those obtained from conventional radio-frequency (RF) glow discharge deposition at low rates (~1 Å/s). However, high quality a-SiGe alloy solar cells are more difficult to achieve at high deposition rates. In this paper, we present the progress made on a-SiGe alloy solar cells by incorporating bandgap profiling and appropriate buffer layers. Using the improved a-SiGe alloy solar cells, a-Si/a-SiGe tandem configurations are made and results presented.

INTRODUCTION

The very high frequency (VHF) glow discharge technique has been widely used in the deposition of amorphous silicon (a-Si) alloy and microcrystalline silicon (μc-Si) materials and devices, such as solar cells and thin film transistors [1-4]. Compared to radio frequency (RF) glow discharge, VHF has the advantage of depositing a-Si alloy and μc-Si at high deposition rates. It is well known that a-Si alloys made with RF glow discharge at high rates exhibit poor quality. The materials contain a high density of defects, microvoids, and dihydride structures. Solar cells made by RF at high rates also show low initial efficiency and poor stability. In production, the deposition rate is usually limited to 2-3 Å/s. In order to reduce the production cost by increasing the deposition rate, new deposition techniques are required. VHF glow discharge is one of the promising techniques. We previously reported that VHF-deposited a-Si alloy solar cells showed good initial efficiency and stability; the performance is largely independent of the deposition rate up to ~10 Å/s [3,4]. We also found that the ion energy is lower and the ion flux is higher for VHF plasma than RF [4]. The high flux of ions with low energies in the VHF plasma is believed to improve the quality of the material. Recently, Takai et al. found that the electron density increases and the electron temperature decreases with the increase of excitation frequency [5]. High temperature electrons in the plasma are associated with the formation of dihydride structures and degrade the stability of the solar cells.

High quality a-SiGe alloy solar cells are usually more difficult to obtain at high deposition rates using RF glow discharge than at low rates. The same problem appears with VHF glow discharge. We reported that the difference between RF low rate cells and VHF high rate cells becomes larger as the germanium content is increased [4]. In this paper, we present our recent improvements of a-Si and a-SiGe alloy solar cells and multi-junction configurations.

EXPERIMENTAL RESULTS AND DISCUSSION

A multi-chamber system with three RF deposition chambers and one modified VHF (MVHF) chamber is used to deposit a-Si and a-SiGe alloy solar cells. The *nip* structures were deposited on stainless steel (SS) substrates with or without Ag/ZnO back reflectors (BR). The intrinsic layers were deposited with a 75 MHz MVHF glow discharge, and the doped layers and buffer layers were deposited with a RF glow discharge. The solar cells were completed with indium tin oxide dots with an active area of 0.25 cm^2 on the *p* layer. The J-V characteristics of the solar cells were measured at 25 ºC under an AM1.5 solar simulator, or for the a-SiGe alloy cells, under AM1.5 solar simulator with a proper long pass filter. The short circuit current was calibrated by quantum efficiency measurements. Stabilized efficiencies were obtained by over 1000 hours of light soaking under 100 mW/cm^2 white light, or white light with a proper long pass filter for a-SiGe alloy solar cells, at 50 ºC.

a-Si alloy solar cells

Table I compares the a-Si alloy solar cells obtained by RF at 1 Å/s and 3 Å/s, and MVHF at 8 Å/s. The short-circuit current densities of these cells are 8.5 to 9.0 mA/cm^2, suitable for the top cell of a triple junction structure. It can be seen from the table that the initial and stabilized efficiencies of the a-Si alloy top cell made with MVHF at 8 Å/s are comparable to the low rate RF top cell, and are much better than the RF 3 Å/s top cell. In addition, we find that the performance of the MVHF a-Si solar cells is not sensitive to the deposition rate up to ~10 Å/s. These results show that MVHF is a promising technique for depositing a-Si alloy solar cells.

Table I. Comparison of high-rate MVHF and low rate RF a-Si alloy top cells on stainless steel substrate with no back reflector.

Technique	Dep. Rate (Å/s)	State	Jsc (mA/cm^2)	Voc (V)	FF	Eff (%)
RF	1	initial	9.03	1.024	0.773	7.15
		stable	8.76	0.990	0.711	6.17
RF	3	initial	8.73	0.967	0.749	6.32
		stable	8.56	0.904	0.646	5.00
MVHF	8	initial	8.84	1.002	0.746	6.61
		stable	8.74	0.960	0.691	5.80

a-SiGe alloy solar cells with MVHF at ~6 Å/s

As shown above, the MVHF a-Si alloy solar cell is almost as good as the RF low rate cell. However, the difference becomes larger for the a-SiGe alloy solar cells [4]. The optimization of MVHF a-SiGe alloy solar cells by improving the deposition conditions, such as ion bombardment, has been previously reported [4]. Here, we present the improvement of a-SiGe alloy solar cells by bandgap profiling and interface buffer layers.

It has been shown that incorporation of proper buffer layers between the intrinsic layer and the doped layers can significantly improve the cell performance, especially for a-SiGe alloy solar cells [6]. However, the buffer layers are very difficult to control precisely with MVHF at high deposition rates. Therefore, most of our high rate a-SiGe alloy cells incorporate RF deposited a-Si alloy p/i and i/n buffer layers. The discontinuity of band gaps may cause high interface defects between the buffer and the intrinsic layers, thus negatively affecting the cell performance. We have therefore incorporated bandgap profiled buffer layers using RF by varying the Si to Ge ratio, resulting in a lower bandgap near the a-SiGe alloy intrinsic layer and a wider bandgap near the doped layer. Table II shows a comparison of the a-SiGe alloy solar cells with standard a-Si alloy buffer layers and a-SiGe alloy bandgap-profiled buffer layers. About a 3% gain in Pmax is obtained for the λ>530 nm performance, which is mainly due to the improved FF.

Bandgap profiling is a very useful technique to improve the performance of a-SiGe alloy solar cells [7]. For high deposition rates, it is more difficult to obtain a proper bandgap profile due to the short deposition time; our previous report showed only a marginal improvement [4]. Recently, we have improved the design and technique of the ramping profile and achieved a gain of 8% in Pmax, which is significantly larger than that obtained previously. Table III summarizes the J-V characteristics of the a-SiGe alloy solar cells with different bandgap profiles. Sample

Table II. Initial J-V characteristics of a-SiGe alloy solar cells made with MVHF at 6 Å/s with a-Si alloy buffers and a-SiGe alloy bandgap profiled buffers. The measurements were made at 25 °C under an AM1.5 solar simulator and with a 530 nm long pass filter.

	Light	Pmax (mW/cm^2)	Jsc (mA/cm^2)	Voc (V)	FF
a-Si buffers	AM1.5	6.66	14.42	0.762	0.606
	>530 nm	4.04	8.92	0.741	0.611
a-SiGe buffers	AM1.5	6.86	14.35	0.762	0.627
	>530 nm	4.15	8.85	0.741	0.633

Table III. Initial J-V characteristics of a-SiGe alloy solar cells made with MVHF at 6 Å/s using different band gap profiling. The measurements were made at 25 ºC under an AM1.5 solar simulator and with a 530 nm long pass filter.

Sample #	Light	Pmax (mW/cm^2)	Jsc (mA/cm^2)	Voc (V)	FF	Profile
9773	AM1.5	6.86	14.35	0.762	0.627	flat
	>530 nm	4.15	8.85	0.741	0.633	
9774	AM1.5	6.80	14.53	0.745	0.628	step
	>530 nm	4.34	9.07	0.730	0.655	
9775	AM1.5	6.93	14.57	0.755	0.630	cont
	>530 nm	4.47	9.09	0.742	0.662	
9778	AM1.5	5.69	13.54	0.731	0.575	over
	>530 nm	3.84	8.51	0.719	0.628	

9773 is a flat band gap (Flat) baseline cell. For sample 9774, GeH_4 and SiH_4 flow rates are changed in three steps (Step) with a higher GeH_4 flow in the region near the *p* layer and a lower flow in the region near the *n* layer. Sample 9775 has a continuous ramping (Cont) with the same average rate as in sample 9774. It is found that a proper profile increases Jsc and FF. The gain in FF is mainly due to the improvement in the long wavelength (λ>530 nm) region. On the other hand, more ramping (Over) decreases the fill factor and leads to a poorer overall cell performance (sample 9778). From this study, we conclude that we have improved the performance of MVHF high rate a-SiGe alloy solar cells by optimizing the bandgap profile. Sample 9775 is the best MVHF high rate a-SiGe alloy solar cell obtained to date. Figures 1 and 2 show the J-V characteristic and quantum efficiency for this sample, respectively.

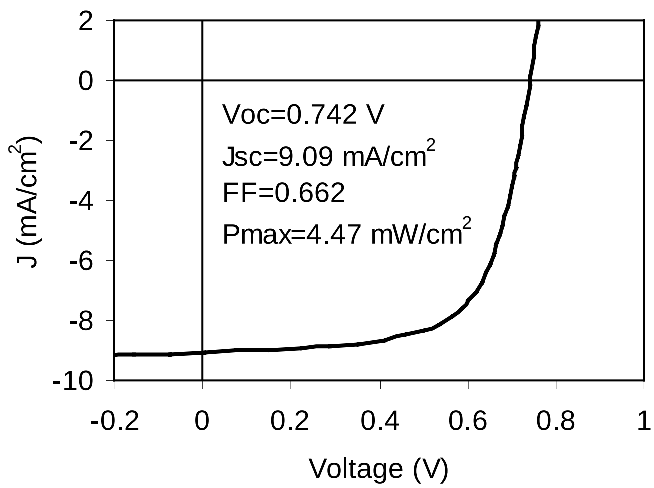

Figure 1. Initial J-V characteristic of the best a-SiGe alloy solar cell made with MVHF at 6 Å/s, measured under AM1.5 with a 530 nm cut-on filter.

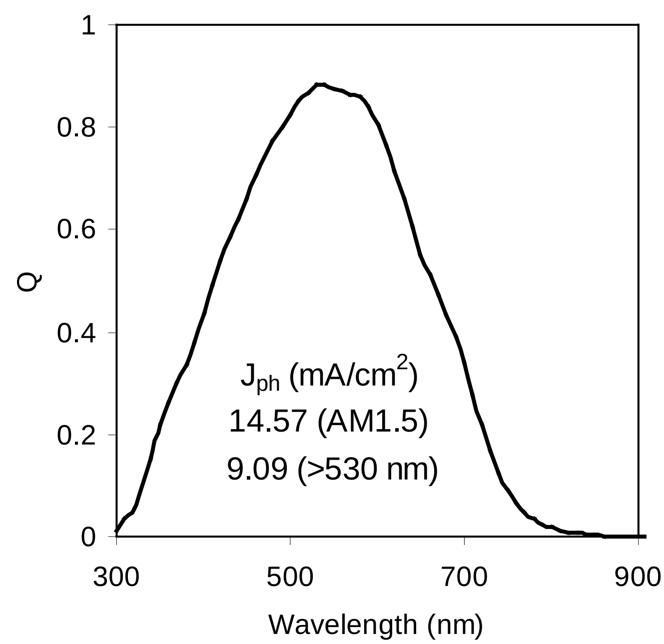

Figure 2. Quantum efficiency of the solar cell in Fig.1.

<u>**a-Si/a-SiGe alloy tandem cells**</u>

Having obtained an improved a-SiGe alloy solar cell at high rate, we then proceeded to make a-Si/a-SiGe alloy tandem structures using a-Si alloy top cells with two different approaches. One uses RF at 1 Å/s and the other MVHF at 8 Å/s. Table IV summarizes the performance of the best solar cells. Sample 9998 was made with MVHF for both the top and bottom cells. Sample 10110 was made using RF at 1 Å/s for the top cell. It is noted that 10110 has better initial and stabilized performance. The difference is partially due to the unoptimized tunnel junction for the MVHF structure. Figure 3 shows the initial J-V characteristic and quantum efficiency of sample 10110, which has a stabilized active area efficiency of 10.2%. The good FF of sample 10110 results from current mismatching, in which the top cell limits the short circuit current.

Table IV. J-V characteristics of a-Si/a-SiGe alloy tandem solar cells using MVHF and RF deposited top cells.

Sample	State	Jsc (mA/cm^2)	Voc (V)	FF	Eff (%)
9998 MVHF	initial	10.1	1.678	0.663	11.2
	stable	9.41	1.613	0.622	9.44
10110 MVHF+RF	initial	9.53	1.731	0.734	12.1
	stable	9.13	1.678	0.667	10.2

SUMMARY

We have made high quality a-Si alloy solar cells using MVHF glow discharge at high deposition rates. The initial performance and stability of the cells are similar to those made with RF at low rates. We have also made significant improvements on high rate a-SiGe alloy solar cells using MVHF at 6 Å/s. This was accomplished by optimizing the buffer layers and bandgap profiling. Using the improved a-SiGe alloy bottom cell, we have achieved a-Si/a-SiGe alloy tandem solar cells having initial 12.1% and stabilized 10.2% active area efficiencies, respectively.

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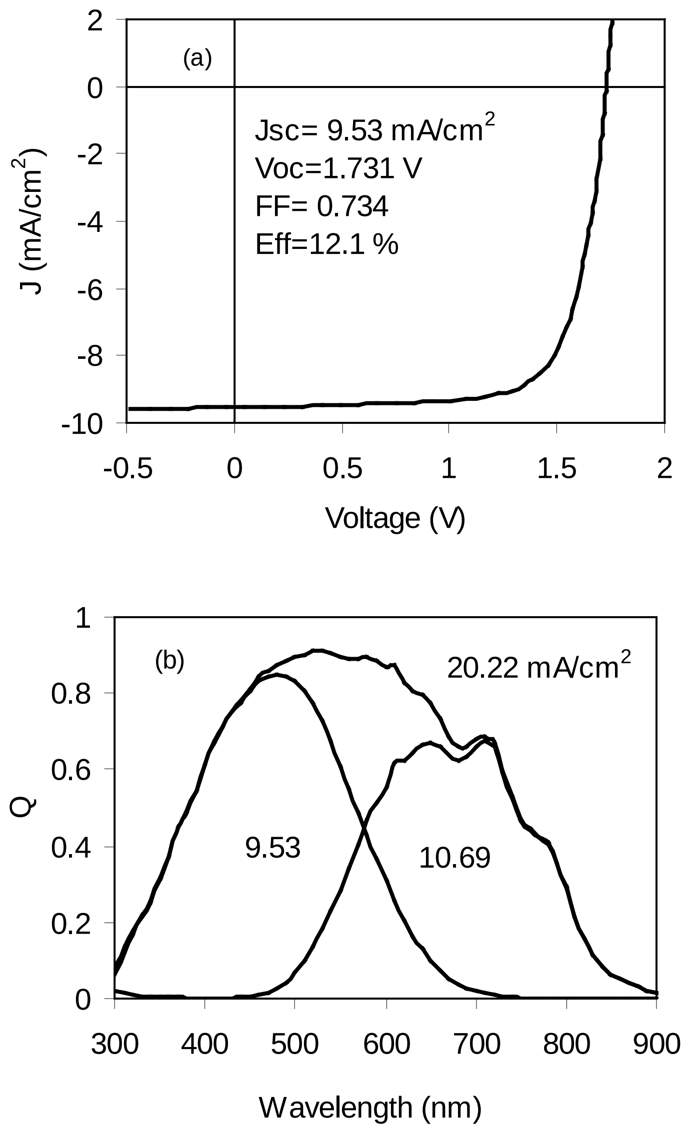

Figure 3. (a) J-V characteristics and (b) quantum efficiency for an a-Si/a-SiGe alloy tandem cell at its initial state.

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