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Amorphous silicon and silicon germanium materials for high-efficiency triple-junction solar cells

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Abstract

In this paper, we report our recent progress in the amorphous silicon (a-Si)-based photovoltaic research program at The University of Toledo (UT). We have achieved the fabrication of (1) wide bandgap a-Si solar cells with an open-circuit voltage of 0.981 and a fill factor of 0.728 using high hydrogen dilution for the i-layer deposition, (2) mid bandgap a-SiGe solar cells having an open-circuit voltage of 0.815 and a fill factor of 0.65, (3) narrow bandgap a-SiGe solar cells with 9.17% initial efficiency, and (4) triple-junction, spectrum-splitting a-Si/a-SiGe/a-SiGe solar cells with 10.6% initial efficiency. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: a-Si; a-SiGe; Solar cells

1. Introduction

Significant progress has been made recently in a-Si photovoltaic research and manufacturing using a triple-junction structure [1–4]. These include the achievement f 15.2% initial efficiency for small area solar cells [1], 13% stable efficiency for small area solar cells [2], 10.2% efficiency for 1 ft 2 solar panels [3] and 8% stable efficiency for 4 ft 2 production scale PV modules [4]. However, in order to meet the long-term efficiency ($> 15\%$) and cost ($< \$50/m^2$) goals [5], there is still a strong need for the study of the materials and device related issues, in particular in the high-efficiency triple-stacked structure.

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We focus our study on the long-term issues related to high-efficiency multiple-junction solar cells. These include the development of high-quality a-Si and a-SiGe related materials and the development and improvement of novel deposition techniques. During the past year, we have established a good baseline for the fabrication of high-efficiency a-Si-based triple-junction solar cells. This paper gives a highlight of our recent research activities in this area.

2. Experimental

Amorphous silicon-based thin film materials are deposited using rf plasma enhanced chemical vapor deposition (PECVD) process in a ultrahigh-vacuum, multi-chamber, load-locked deposition system. There are two deposition chambers in this system, with one dedicated to the growth of a-Si and a-SiGe intrinsic materials, and the other to the growth of n-type, a-Si and p-type microcrystalline silicon (μc-Si) layers. Mixtures of Si_2H_6 (Si_2H_6 and GeH_4) and H_2 are used for the deposition of a-Si (a-SiGe) materials. Mixtures of BF_3 (PH_3), SiH_4 and H_2 are used for the deposition of p-layer μc-Si (n-layer a-Si) layers to form the a-Si n–i–p junctions. Stainless steel (SS) foils, 0.13 mm thick, with and without a textured Ag/ZnO back-reflector coating, are used as substrates for the solar cell fabrication. Since we deposit both n-layer and p-layer materials in the same chamber, we pre-coat the chamber under typical p-layer growth conditions for 5 min before substrates are moved in for the p-layer growth.

ITO layers, serving as the top electrodes and anti-reflecting coatings, are deposited in an rf sputtering chamber from In_2O_3/SnO_2 targets having 5%, 10% and 15% SnO_2 composition. Aluminum grids are evaporated in vacuum at room temperature to improve the current collection.

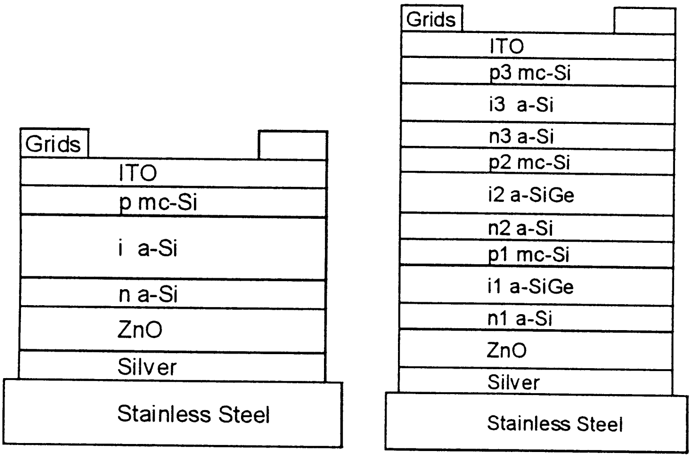
Current–voltage characteristics and quantum efficiency curves for these solar cells are measured at UT using ELH lamps which is somewhat red rich. At the moment, many samples including those with I–V curves quoted in this paper were measured at Energy Conversion Devices, Inc. (ECD) using a Xenon solar simulator.

3. Results and discussions

To improve the efficiency of triple-junction solar cells, we have divided our research into several sub-task areas: wide bandgap research, mid bandgap research, narrow bandgap research, non-semiconductor research and multi-junction solar cell fabrication. The device structure for single and triple cells are shown in Fig. 1(a) and (b).

3.1. Wide bandgap research

We deposited wide bandgap a-Si alloy solar cells having structure of SS/Ag/ZnO/a-Si n^+/a-Si-intrinsic/μc-Si-p^+/ITO. Various deposition conditions for the i-layer and p-layer were explored. A high hydrogen dilution and relatively low temperature were



(a) (b)

Fig. 1. Schematics of the single-junction (a) and triple-junction (b) structures of a-Si solar cell devices fabricated in this program.

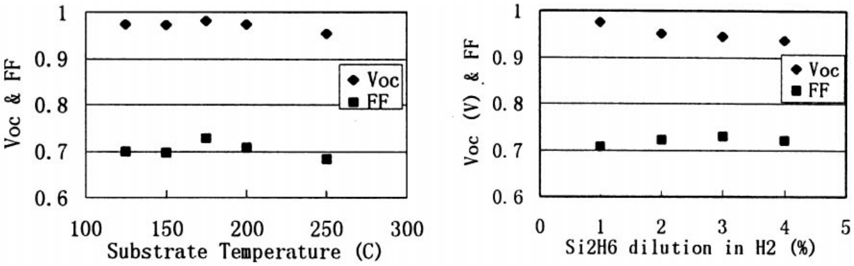


Fig. 2. (a) Variation of V_{oc} and FF with T_s for 1% Si_2H_6 in H_2. (b) Variation of V_{oc} and FF with Si_2H_6 dilution in H_2 at $T_s = 200°C$.

used for the i-layer deposition [6,7]. Fig. 2 illustrates the variations of open-circuit voltage (V_{oc}) and fill factor (FF) of the devices with substrate temperature T_s for 1% Si_2H_6 diluted in H_2 (2a), and with Si_2H_6 dilution for a fixed $T_s = 200°C$ (2b). After optimization, we have obtained a-Si single-junction solar cells with a V_{oc} of 0.981 V and FF of 0.728.

3.2. *Mid bandgap research*

In the mid bandgap research area, we have explored various deposition conditions to improve the solar cell J_{sc} while maintaining reasonably high V_{oc}. We have investigated a series of a-SiGe mid bandgap cells with i-layer deposited at different ratios of GeH_4/Si_2H_6 from 0.24 to 0.47, with and without Ge content grading, and dilution in H_2 ranging from 1.5% to 2.5%. Some of the results are summarized in Table 1.

Table 1
Device data for a series of a-SiGe mid solar cells having i-layers deposited under different deposition conditions, measured using an ELH lamp

Sample	Ratio of GeH_4/Si_2H_6	% in H_2	Ge grading	V_{oc} (V)	FF %	J_{sc} mA/cm^2	Substrate
Gd286	0.36	2.5	No	0.824	64.14	17.94	SS
Gd285	0.36	2.5	Yes	0.810	64.62	18.16	SS
Gd302	0.40	2.0	No	0.815	62.29	18.14	SS
Gd303	0.40	1.5	No	0.815	62.93	18.54	SS

Table 2
Photovoltaic parameters of narrow band gap solar cells with different buffer layers, measured using an ELH lamp

Samples	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	P_{max}(mW/cm^2)
GD180 Standard	0.647	23.5	0.506	7.69
GD202 w/a-SiGe buffer	0.662	21.6	0.534	7.64
GD203 w/graded a-SiGe buffer	0.680	23.4	0.536	8.53
GD209 w/graded a-SiGe buffer	0.675	24.3	0.559	9.17

3.3. Narrow bandgap research

A high-quality narrow-bandgap material is critical to the achievement of high-efficiency triple-junction solar cells. To achieve high-conversion efficiency, an a-SiGe absorber layer is usually sandwiched between two thin a-Si buffer layers which are in direct contact with the p- and n-doped layers. These a-Si buffer layers are found to enhance the performance of a-SiGe solar cells [8]. However, even with these a-Si buffer layers, there are still abrupt discontinuities in the bandgap at the interfaces between these buffer layers and the a-SiGe absorber layer. Therefore, we performed a study on the insertion of additional a-SiGe interface layers (with less Ge compared with the absorber) which reduces the bandgap offset.

Table 2 lists the photovoltaic parameters of V_{oc}, J_{sc}, FF and the maximum power output P_{max} of a-SiGe solar cells with different interfacial buffer layers. GD180 is a standard a-SiGe device and GD202 contains a-SiGe buffer layers with a fixed Ge content inserted between the a-Si buffer layers and a-SiGe i-layer at both the n- and p-interfaces, while GD203 and GD209 have Ge-content graded buffer layers at both interfaces. It is clearly seen that the V_{oc} and FF have increased after the introduction of the additional a-SiGe interfacial layers and the improvements are approximately in the range of 2–5% for V_{oc} and 5–10% for FF. The V_{oc} and FF enhancement is higher for graded buffer layers. Therefore, the J–V characteristics of GD180 and GD209 are compared in Fig. 3. The enhancement in V_{oc} and FF result in a net increase in device P_{max}.

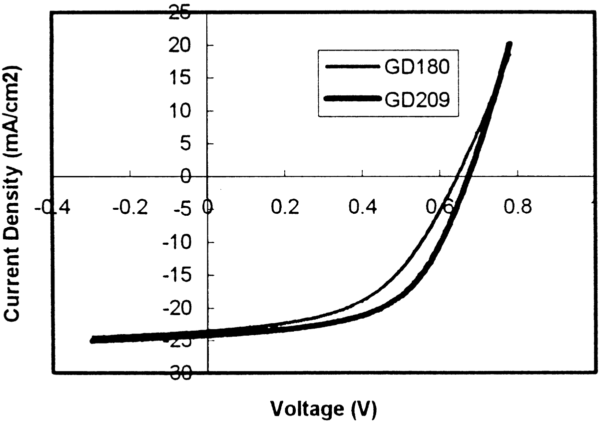


Fig. 3. Illuminated J–V characteristics of GD180 and GD209 samples.

3.4. *Non-semiconductor materials research*

We studied rf sputter deposition of ITO films for use as the top electrodes and anti-reflecting coatings. The results suggest that good quality ITO films, with a sheet resistance less than 50 Ω and an absorption coefficient less than 10^3 cm^{-1}, could be deposited at elevated temperature (225°C–250°C) and low pressure (~ 8 mTorr) with an RF power of 30–50 W for a 2″ target. ITO targets with different In_2O_3 and SnO_2 compositions were studied. Our preliminary results suggest that ITO films produced using a target with 90% In_2O_3 and 10% SnO_2 demonstrates higher quality. The detailed results of the ITO study were reported in the Second World Conference and Exhibition on Photovoltaic Energy Conversion [9].

3.5. *Fabrication of triple-junction amorphous silicon solar cells*

Using the preliminary optimized component cells and the sputter deposited ITO as described above, we fabricated a series of triple-junction solar cell devices, having a structure shown in Fig. 1(b). Fig. 4 is a J–V curve for such a triple-junction solar cell measured at Energy Conversion Devices, Inc. (ECD) under a solar simulator light, showing a 10.6% initial efficiency. Fig. 5 is the QE curve for the triple-cell measured at ECD, showing a high integrated-total current of 23.6 mA/cm^2.

4. Summary

Within a relatively short time period, we have established a good baseline for our triple-junction solar cell fabrication. We have achieved the deposition of high-quality component cells. Using these optimized a-Si and a-SiGe cells, we fabricated

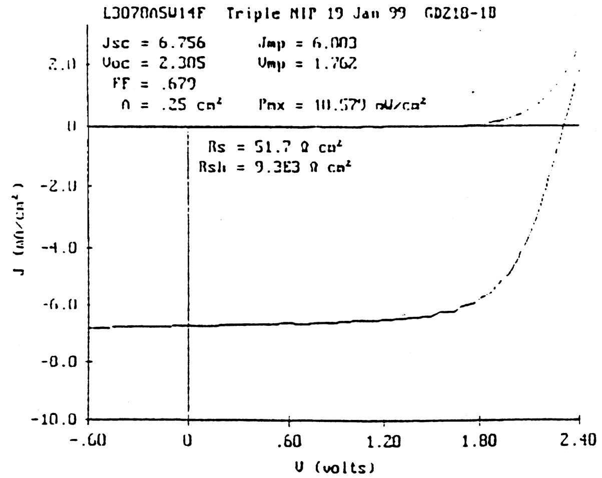


Fig. 4. *J*–*V* curve of a triple-junction solar cell with an initial efficiency of 10.6%.

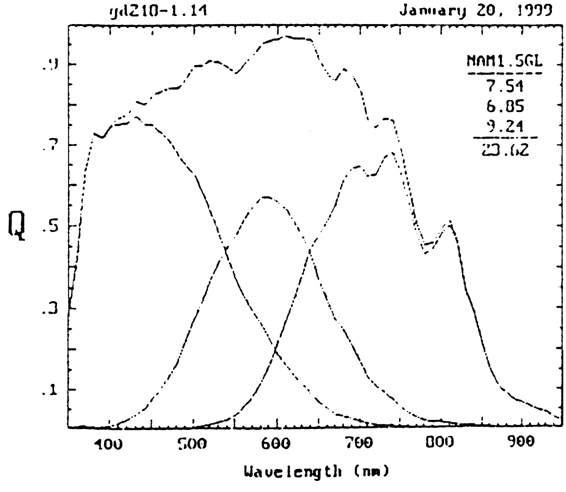


Fig. 5. QE curves of a triple cell showing an J_{QE} of 23.6 mA/cm^2.

triple-junction, spectrum-splitting, a-Si/a-SiGe/a-SiGe solar cells with 10.6% initial efficiency.

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