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High-Quality 10 Å/s Amorphous Silicon Germanium Alloy Solar Cells by Hot-Wire CVD

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ABSTRACT

High-quality high-deposition-rate (10 Å/s) amorphous silicon germanium (a-SiGe:H) alloy solar cells have been made by hot-wire chemical-vapor deposition (HWCVD). HW a-SiGe:H alloys are evaluated in the SS/n-i-p/ITO solar cell configuration, where the n- and i-layers are deposited by HWCVD at NREL and the p-layer by conventional glow discharge in a separate reactor by United Solar. Effects of Ge concentration, hydrogen dilution, substrate temperature, and step-wise bandgap profile in the i-layer have been studied and optimized. The best cell has an average optical bandgap of 1.6 eV with a low H-dilution at 250°C and a 3-stepwise bandgap profile where the narrowest bandgap is near the p-i interface. The best initial power output has exceeded 4 mW/cm^2 under AM 1.5 illumination with a λ>530-nm filter. When combining with a USSC a-Si:H top solar cell, the best double-junction solar cell exhibits an initial 11.7% active-area efficiency, and a 9.6% stable efficiency after 1000 hours of one-sun light soaking.

1. Introduction

Hydrogenated amorphous silicon-germanium (a-SiGe:H) alloy accounts for over half the materials in most commercial multi-junction amorphous-silicon thin-film solar cells. a-SiGe:H has used in the tandem and triple-junction solar cells to improve the red response. Various techniques have been tried to improve the property of the a-SiGe:H alloy. Growing a-SiGe:H alloy near the threshold of microcrystallinity using hydrogen dilution at low deposition rate (~1 Å/s) by rf plasma-enhanced CVD (PECVD) [1] and applying graded alloy layers are two of many techniques that have significantly improved a-SiGe:H solar cell performance. Despite the recent development of microcrystalline silicon (μc-Si) solar cells and their potential to replace a-SiGe:H materials, a-SiGe:H solar cells exhibit a higher open-circuit voltage (V_{oc}), a tunable bandgap, and potential for further improvement. With these considerations, a-SiGe:H alloys are still considered as promising materials used in commercial a-Si:H-based solar cells fabrications.

Deposition rate is one of the important factors to increase the throughput and reduce the capital cost for PV production. It is even more crucial for a-SiGe:H because of the large amount of materials used in the solar cells and the high cost of germane gas. The best a-Si:H-based solar cells are made at a deposition rate of about 1 Å/s. Presently, the properties of the high-deposition-rate (greater than 1Å/s) materials remain inferior to those deposited at 1 Å/s. The efficiency of the high -rate solar cells, as a consequence, is lower than the at 1 Å/s cells. High-rate materials, solar cells, and growth mechanisms have received great attention because of the technical importance. Various deposition techniques such as electron cyclotron resonance, microwave, modified-VHF, and HWCVD have been examined [2, 3]. Solar cells deposited at over 100 Å/s also reported [4, 5]. In this paper, we report on a collaborative effort to study HW a-SiGe:H midgap n-i-p solar cells between United Solar and NREL. An efficient high-rate a-SiGe:H n-i-p solar cell has been demonstrated.

2. Experimental

Solar cells in a SS/n-i-p/ITO configuration were made, with the n- and i-layers deposited at 300°C, by HWCVD at NREL in the dopant chamber and i-chamber of the T-system [6], respectively; then the unfinished solar cells - sealed in a N_2 filled bag - were shipped to United Solar for the deposition of the microcrystalline p-layer and the top ITO contact.

The evaluation of the final solar cells was done at United Solar. Maximum power after a 530-nm band-pass filter was measured to simulate the middle cell in a triple-junction configuration. This is a routine measurement at United Solar for the middle gap cells. The cell has an area of 0.25 cm^2 defined by ITO, with a Au finger on top to improve the current collection. For this purpose, the cell was deposited on the stainless steel without back reflector.

Effects of Ge content, substrate temperature, hydrogen dilution, and bandgap profile have been studied and optimized. Pure GeH_4 and SiH_4 gases were used in this study. The thickness of the intrinsic layer was kept about at 2000 Å. The deposition rate of a-SiGe:H by HW is greater than 10 Å/s. We later incorporated the optimized HW a-SiGe:H solar cell into the double-junction configuration, combined with United Solar's optimized top cell. The SS substrate with Ag/ZnO back-reflector was used. The degradation of the double-junction cell was performed at United Solar with a one-sun light source.

3. Results and Discussion

The graded a-SiGe:H i-layer has been examined in the past and solar cell performance has been improved [7]. Figure 1 shows the schematic of a graded a-SiGe:H cell in our n-i-p solar cell structure. The wide-gap a-Si:H was deposited first on the n-layer and then the decreasing bandgap a-SiGe:H. This structure helps hole collection by placing the narrowest bandgap near the p-i interface. The holes generated in the worst materials do not need to travel far to the p-layer. Therefore, this design improves the hole collection. Note that the quality of the materials degrades when more Ge incorporated into the film. The film of optimized H-diluted graded a-SiGe:H used in the solar cell was deposited on glass and c-Si substrates. This 9000-Å film has shown a photo-to-dark ratio of greater than 10^5, with 10% H-content from FTIR measurement, and an average optical bandgap (E_T) of 1.6 eV.

Growing a-SiGe:H alloy near the threshold of microcrystallinity using hydrogen dilution at low deposition rate (~ 1 Å/s) by rf plasma-enhanced CVD [8, 9] and applying a graded alloy layer is one of the many techniques that have significantly

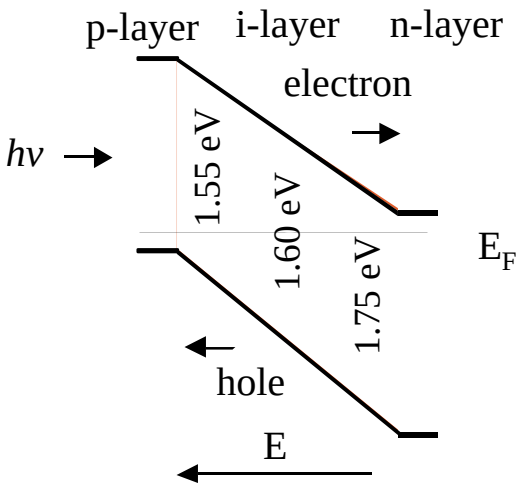

Figure 1. Diagram of graded a-SiGe:H i-layer in n-i-p solar cell.

improved a-SiGe:H solar cell performance. We mentioned earlier that materials grown near the transition from amorphous to microcrystalline have shown superior properties. To make the near edge materials, hydrogen was added to the mixture of SiH_4 and GeH_4. The deposition rate was decreased as a result of H-dilution. We use a low hydrogen-to-SiH_4 ratio, and the deposition rate is about 10 Å/s.

Table I shows the best HW a-SiGe:H midgap n-i-p solar cell whose H-diluted and graded active layer was deposited at 10 Å/s on the bare SS substrate. J-V characteristics are measured under AM1.5 illumination with and without a λ>530-nm filter. The best initial efficiency at AM1.5 is over 7%. Using the H-dilution and graded i-layer, FF has changed from below 0.600 to 0.676. More importantly, the initial power output after the 530-nm filter exceeded 4 mW/cm^2, which is usually used as an indicator for a good-quality middle-gap cell even for low rate (1 Å/s) a-SiGe:H middle cells.

Table I. Performance of n-i-p solar cell with 10 Å/s HW a-SiGe:H active layer

Solar Spectra	P_{max} (mW/cm^2)	V_{oc} (V)	FF	J_{sc} (mA/cm^2)
AM1.5	7.28	0.792	0.676	13.6
λ>530 nm	4.21	0.769	0.677	8.08

Table II. Performance of a-Si:H and a-SiGe:H double-junction solar cell

State (hour)	P_{max} (mW/cm^2)	V_{oc} (V)	FF	J_{sc} (mA/cm^2)
initial	11.7	1.800	0.748	8.66
1050	9.62	1.742	0.671	8.18

Finally, this optimized midgap cell was incorporated into a double-junction SS/n-i-p-n-i-p/ITO structure to test the validation of its performance. The top cell is an optimized United Solar a-Si:H solar cell grown at 1 Å/s. The bottom cell is NREL's optimized HW a-SiGe:H solar cell at 10 Å/s. The best cell achieved an initial active- area efficiency of 11.7% with V_{oc} of 1.805 V, FF of 0.748,

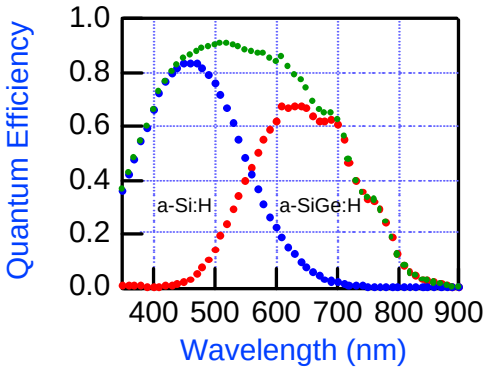

Figure 2. Quantum efficiency of the best double-junction solar cell.

and J_{sc} of 9.21 mA/cm^2 with QE correction (see Table II.) Figure 2 shows the QE data. After 1000 hours of one-sun light soaking, this cell stabilized at 9.6% efficiency.

4. Summary

In conclusion, a collaborative effort between NREL and United Solar produced a high-performance midgap solar cell whose active layer is deposited by HWCVD at 10 Å/s. A power output of 4.2 mW/cm^2 was measured through a 530-nmlong pass filter. The best double-junction cell that combines United Solar's best a-Si:H top cell and the optimized HW a-SiGe:H midgap cell exhibits an initial 11.7% and stable 9.6% active-area efficiency. This new result shows the potential of fabricating high-efficiency amorphous silicon solar cells at higher deposition rates—an important result for low-cost production of PV modules.

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