

Thinner silicon-based tandem solar cell with high efficiency made by hot wire CVD

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Received 30 November 2010, revised 21 December 2010, accepted 25 December 2010
Published online 22 July 2011

Keywords tandem cells, thin film solar cells, hot wire CVD

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We developed thin film silicon tandem cells with hot-wire deposited amorphous (protocrystalline) and nanocrystalline i-layers, with a total thickness of only 1.43 μm . This is considerably thinner than the thickness of 2.5–3.0 μm normally needed, which is important to significantly reduce production costs for this type of cells. An initial efficiency of 8.84% was obtained. The top cell is ~ 220 nm and the bottom cell only ~ 1210 nm thick. No

intermediate reflector layer is introduced. Compared to standard PECVD tandem cells, the V_{oc} is remarkably high, consistent with the beneficial effect of thin i-layers on V_{oc} and with the high V_{oc} of 0.57 V obtained for single junction HWCVD nc-Si:H cells. After over 2000 hours of light soaking, a stabilized efficiency of 7.63% was obtained.

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1 Introduction Hot-Wire Chemical Vapor Deposition (HWCVD) is a low-cost, high deposition rate alternative for commonly used plasma-based deposition techniques. In HWCVD, an assembly of hot catalytic transition metal wires provides an efficient and distributed source of primary radicals. The high atomic hydrogen flux from the wires further aids in reaching a silane utilization ratio in excess of 80%. As the HWCVD technique does not use radio frequency (RF) or very high frequency (VHF) power supplies, there are no high frequency electromagnetic fields, and thus scaling up is not hampered by finite wavelength effects or the need of rigorous grounding and shielding requirements to avoid inhomogeneous electrical fields.

Since the dangling bond density increases considerably [1] due to prolonged illumination, the electronic properties of amorphous silicon degrade as a result of this, which is called the Staebler-Wronski effect (SWE). However, lower degradation is generally observed for thin amorphous silicon cells when compared to thicker ones. The SWE was significantly reduced further for protocrystalline silicon solar cells [2, 3]. In addition to the improved stability, thinner solar cells lead to cost reduction, in particular if an inter-

mediate reflector layer can be avoided in ‘micromorph’ tandem cells.

Combining the above advantages, this paper presents the recent results we obtained for extraordinary thin tandem solar cells with high efficiency made by HWCVD.

2 Experiment details The cell structure is of the superstrate type: glass/Asahi U-type $\text{SnO}_2\text{:F/a-Si}$ top cell/nc-Si bottom cell/ ZnO:Al/Ag . Amorphous (protocrystalline) and nanocrystalline intrinsic films were made in our multi-chamber UHV system, PASTA [4], by HWCVD using tantalum wires, while all doped layers were deposited by PECVD at 13.56 MHz in the other chambers of the same setup. The p-layer of the top cell was an a-SiC:H layer made by introducing methane to the feedstock gases. The bottom cell i-layer was made in three steps, keeping hydrogen gas flow constant at 100 sccm and slightly increasing the H_2 dilution ratio (defined as $\text{H}_2/(\text{SiH}_4+\text{H}_2)$) from 95.0% to 95.2% by reducing the SiH_4 flow, to acquire nanocrystalline silicon with a constant crystalline fraction over the thickness of the layer.

The thickness of the material and solar cells were measured with a Dektak surface profiler. A Reflection-Transmission (RT) system was used to measure the reflectance and transmittance from which the optical bandgap of the protocrystalline materials can be derived. The Urbach energy and defect density were obtained from the combination of RT and constant photocurrent method (CPM) measurements. A calibration constant of 10^{16} was used from [5] to determine defect density from the value of the absorption coefficient at 1.2 eV.

Current-voltage characteristics of the solar cells were measured under AM1.5 100 mW/cm² white light generated by a dual beam solar simulator (WACOM) at an ambient temperature of 25 °C. The external collection efficiency was measured with a spectral response setup in the dark as well as under light bias conditions. Light-soaking experiments were performed to measure the degradation of the solar cells during illumination. The illumination intensity was kept at 90 mW/cm²; the temperature was stabilized at 50 °C; the cells were degraded under open circuit conditions.

3 Result and discussion A high quality protocrystalline intrinsic layer was made by HWCVD using 2 tantalum wires and pure silane (no H₂ dilution). An optical bandgap of 1.9 eV and activation energy of approximately 0.9 eV was obtained for such a layer, which means that the material is perfectly intrinsic. The quality is further confirmed by the Urbach energy of 58 meV and a defect density of just 1×10^{17} cm⁻³. As the dark conductivity of the material is as low as 3.2×10^{-12} S/cm, a photoresponse (ratio of photoconductivity and dark conductivity) of 10^7 is obtained.

The thickness of the tandem solar cell is as low as 1.43 μm, which is much thinner than the thickness of more than 2.5 μm normally needed. We made top cell material separately and acquired a top cell thickness of around 220 nm, thus the bottom cell thickness in the tandem cells is calculated to be approximately 1210 nm.

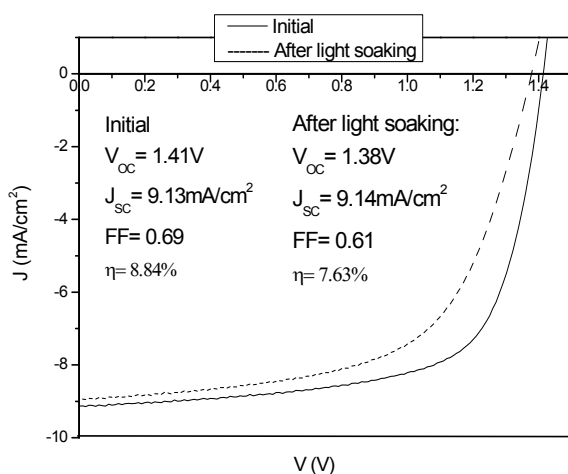


Figure 1 I-V characteristics of the tandem cell before and after light soaking for over 2000 hours.

The short circuit current (J_{sc}) and open circuit voltage (V_{oc}) improvements of these thin tandem solar cells after an annealing treatment prior to light soaking and after light soaking are derived from the current-voltage measurement results as plotted in Fig. 1. We observe an extraordinarily high V_{oc} (1.41 V) and a high initial tandem cell conversion efficiency of 8.84%. The superb V_{oc} is first of all due to the relatively high band gap of the protocrystalline intrinsic layer [6]. Further, the a-SiC:H p-layer, the undoped buffer layer at the i-p interface of the top cell, and the optimizations in our previous work on single junction HWCVD nc-Si:H cells also contribute to the V_{oc} [7].

Under light soaking conditions the FF declined by 11.6%, while J_{sc} slightly increased (by less than 2%). Larger changes were observed in the series resistance (R_s , by 85.2%) and the parallel resistance (R_p , by 17.7%), which have large influence on FF. The deterioration of R_s might be due to the deterioration of the Ag contact layer in air, which is caused by the absence of an encapsulation layer. The observed improvement of the R_p in the first ten hours is not yet understood, but obviously is an advantage for this type of cell because it limits the decrease of the FF and reduces shunting (Fig. 2).

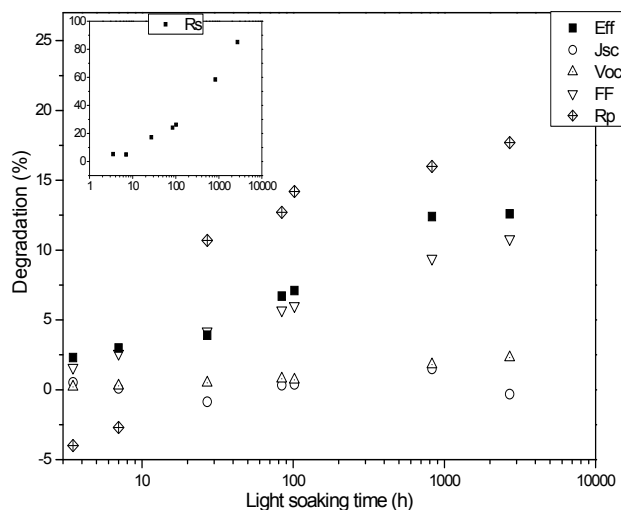


Figure 2 Light induced relative degradation versus light soaking time for the tandem solar cell parameters.

The efficiency of the cell shows complete stabilization after a relative degradation of 13.6%, owing to the improvement in R_p . The degradation is almost solely due to the fill factor. We attribute the continuing decrease in FF to the increase in series resistance caused by Ag contact deterioration. This can be avoided by proper encapsulation. J_{sc} and V_{oc} are very stable, showing variations within 3% relative. As shown in Fig. 3, the external collection efficiency of our thin tandem solar cell shows almost no degradation, consistent with the stable J_{sc} . The thinner i-layer plays a

positive role in this behaviour, as collection of photo-generated carrier remains complete after light soaking. The behaviour of the tandem cell under light soaking is dominated by the top cell, which is the current limiting cell of the tandem cell (as was calculated from the external collection efficiency (ECE) spectra in Fig. 3). The integrated current of the top and bottom cell from the ECE curves is 9.02 mA/cm^2 and 9.61 mA/cm^2 , respectively. This means that the tandem cell can be made even more stable without sacrificing efficiency by making it bottom cell current limited.

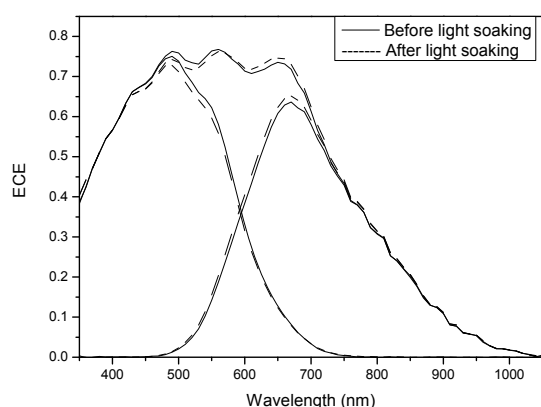


Figure 3 External collection efficiency spectra at 0 V of the thin tandem solar cell before and after light soaking for over 2000 hours.

4 Conclusions Thin a-Si:H/nc-Si:H tandem cells with a thickness of only $1.43 \mu\text{m}$ were made. The tandem cell shows a relatively high efficiency of 8.84%. The lower thickness proved to be helpful to acquire outstandingly low light-induced degradation, of only 12.6%. J_{sc} and V_{oc} showed an excellent stability under light soaking, while the efficiency degradation was almost entirely due to a decrease in the FF, dominated by the current-limiting top cell. Work is ongoing on making the bottom cell current limiting, which should lead to even better stabilized efficiency.

Acknowledgements J. X. acknowledges the financial support from the Chinese Scholarship Council (CSC).

References

- [1] D. L. Staebler and C. R. Wronski, *Appl. Phys. Lett.* **31**, 292 (1977).
- [2] R. J. Koval, J. Koh, Z. Lu, L. Jiao, R. W. Collins, and C. R. Wronski, *Appl. Phys. Lett.* **75**, 11 (1999).
- [3] J. Koh, Y. Lee, H. Fujiwara, C. R. Wronski, and R. W. Collins, *Appl. Phys. Lett.* **73**, 1526 (1998).
- [4] R. E. I. Schropp, K. F. Feenstra, E. C. Molenbroek, H. Meiling, and J. K. Rath, *Philos. Mag. B* **76**, 309 (1997).
- [5] K. Pierz, W. Fuhs, and H. Mell, *Philos. Mag. B* **63**, 123 (1991).
- [6] R. E. I. Schropp, M. K. van Veen, C. H. M. van der Werf, D. L. Williamson, and A. H. Mahan, *Mater. Res. Soc. Symp. Proc.* **808** (2004), A8.4.1.
- [7] M. K. van Veen, C. H. M. van der Werf, J. K. Rath, and R. E. I. Schropp, *Thin Solid Films* **430**, 216 (2003).