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Thin film silicon modules on plastic superstrates

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Abstract

The aim of this research is to fabricate high efficiency a-Si/μc-Si tandem solar cell modules on flexible (polymer) superstrates using the Helianthos concept. As a first step we began by depositing the top cell which contains an amorphous silicon (a-Si:H) i-layer of ∼350 nm made by VHF PECVD at 50 MHz in a high vacuum multichamber system called ASTER, with hydrogen to silane gas flow ratio of 1:1. Such amorphous cells on-foil showed an initial active area (0.912 cm^2) efficiency of 7.69% ($V_{oc} = 0.834$ V, FF = 0.71). These cells were light soaked with white light at a controlled temperature of 50 °C. The efficiency degradation was predominantly due to degradation of FF that amounted to only 11% after 1000 h of light soaking. The cell-on-foil data prove that thin film silicon modules of high stability on cheap plastics can be made at a reasonable efficiency within 30 min of deposition time. A minimodule of 8 × 7.5 cm^2 area (consisting of 8 cells interconnected in series) with the same single junction a-Si:H p–i–n structure had an initial efficiency of 6.7% ($V_{oc} = 6.32$ V, FF = 0.65).

PACS: 81.15.Gh; 81.07.Bc; 81.05.Bx

Keywords: Silicon; Solar cells; Photovoltaics

1. Introduction

High efficiency thin film silicon based solar cells require a fabrication process in a temperature regime that is optimum for thin film silicon growth (∼200 °C). The aim of this work is to deposit our high efficiency a-Si:H/μc-Si:H tandem solar cells on a temporary temperature-resistant superstrate and transfer them to permanent plastic superstrates. This type of cells have already reached 12% initial and 11.4% stabilized efficiencies on Asahi U-type SnO_2:F coated glass [1]. The fabrication of thin film devices on temperature sensitive substrates, such as plastic, can be done in two ways: (i) Direct deposition on the substrates at low temperature. Moreover, a mild gas phase process is needed for a sensitive substrate. (ii) Deposition on a temporary substrate that is resistant to high temperature as well as reactive gas species and transfer of the cell to a permanent substrate. In this paper we are dealing with the latter type, by which it is possible to obtain solar cells with high efficiency, as the deposition of the silicon layers are at their optimum thermodynamic conditions [2]. The present fabrication steps involve the deposition of thin film silicon cells by very high frequency plasma enhanced chemical vapour deposition (VHF PECVD), on SnO_2:F-coated aluminium foil (provided by Helianthos b.v.), which were then transferred to a plastic substrate at Helianthos b.v.

This Helianthos concept of manufacturing of flexible thin film silicon modules was originally invented by researchers at Akzo Nobel and Utrecht University, and was first published in 1998 [3]. After a successful proof of the concept [4] that showed 6.1% efficiency for a-Si:H solar cells on a small area, solar modules have been made by the

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Helianthos concept with p–i–n cells deposited by RF PECVD at 13.56 MHz, which is the standard deposition process at present in the pilot production stage at Helianthos b.v. For 60 cm^2 aperture area series-connected modules, an initial efficiency of 8% and a stabilized efficiency of 6.5% for a-Si:H single junctions made in a prototype reactor [5] were reported. The modules showed degradation of 19%, which is typical for a-Si:H cells. Later, modules made from the pilot roll-to-roll system at Helianthos b.v. reached initial efficiencies around 6% for an aperture area of 840 cm^2 [6]. These results have already proved the excellent industrial viability of the Helianthos concept and pave the way to further improvements as far as efficiency and deposition rate is concerned. After a successful demonstration of an a-Si:H/a-Si:H tandem module with stabilized efficiency of 7% [5], a micromorph (a-Si/μc-Si) module based on the tandem concept, for which the silicon layers were made at IPV Jülich and the modules were fabricated at Helianthos, has been reported [7]. An initial efficiency of 9.4% shows promise of an a-Si:H/μc-Si:H tandem structure by the Helianthos module concept. All of the above results are based on depositions by standard RF PECVD (13.56 MHz). Further improvement in the efficiency and deposition rate are expected with VHF PECVD deposition process, a technique that has delivered the best efficiencies in laboratory scale, both for μc-Si cell as well as a-Si:H/μc-Si:H tandem cells, especially at high deposition rates. This paper gives our initial experience with the module fabrication with silicon layers made by VHF PECVD in a laboratory scale deposition system called ASTER at Utrecht University. The aim is to make high efficiency a-Si:H/μc-Si:H tandem cells and modules on flexible foils. In this paper we show only the single junction top cell (amorphous silicon cell made by VHF PECVD at 50 MHz at substrate temperature of around 200 °C) on foil. The deposition by VHF allows high quality intrinsic as well as doped layers to be made at high rates, which is important for industrial production. The fabrication of an a-Si:H/μc-Si:H tandem cell and module on foil using VHF PECVD is in progress.

2. Experimental

2.1. Module fabrication

The module fabrication at Helianthos b.v. goes through different steps starting with (1) the TCO layer deposition on Al foil by a roll-to-roll process, followed by (2) p, i, and n silicon layers by RF PECVD roll-to-roll deposition, (3) deposition of a ZnO:Al/Al back reflector, (4) roll to roll monolithic series integration, (5) transfer to permanent polymer substrate through roll-to-roll lamination, (6) removal of the temporary superstrate by wet etching in a roll-to-roll process and (7) roll-to-roll encapsulation. For the lab module studied here, only step (1) has been done in a roll-to-roll process to deposit SnO_2:F layer by atmospheric pressure chemical vapour deposition (APCVD) on Al foil at Helianthos b.v. All the silicon layers were deposited in laboratory batch type reactors in an ultra high vacuum deposition multichamber system called ASTER at Utrecht University, on 10×10 cm^2 area substrates, cut out from the 35 cm wide TCO coated foil roll. The deposition technique used here is VHF PECVD at 50 MHz at a substrate to electrode distance of 27 mm. The sample is then sent to Helianthos b.v. to complete the rest of the module fabrication processes, i.e., DC pulsed sputtering of ZnO:Al and Al for back reflector, laser scribing by an Nd:YAG laser on an *X–Y* table and monolithic integration, transfer to a polymer substrate and etching of temporary substrate (Al) by alkaline solution.

In the text here we describe two types of devices.

(i) Cell-on-foil: These are individual cells of ~1 cm^2 area on foil (plastic). The actual (active) cell area is 0.912 cm^2, due to the area loss in the scribing process. These cells are not encapsulated. The active area efficiencies are reported for such cells to make a comparison with the cells on glass.
(ii) Complete series interconnected mini module of size 8×7.5 cm^2 (aperture area 60 cm^2) consisting of 8 cells (Fig. 1). As is shown below, there is only a small difference in efficiency between the single cells and the module. The area loss due to scribing (dead area) is 8%. We present the aperture area efficiency for these modules.

2.2. Characterisation

The *I–V* characteristics of the cells and modules were measured by a dual beam solar simulator (Wacom Co., Japan) with a calibrated AM 1.5 simulated light spectrum. The cells and modules were light soaked with white light at

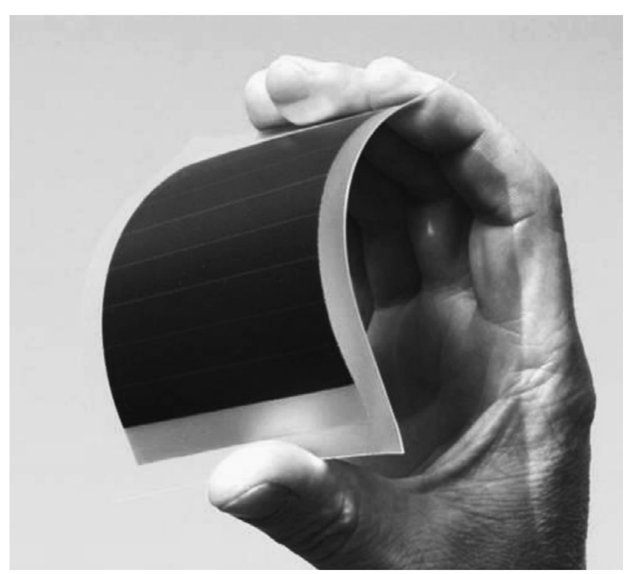

Fig. 1. Minimodule consisting of 8 cells in series with an aperture area of 60 cm^2.

50 °C. Structural properties of the samples were studied by cross-sectional transmission electron microscopy (XTEM). Bright field (BF) images were made for the cross-section of the cells and the void structures were further studied by imaging in defocused mode. Selective area diffraction pattern (SDPC) images were recorded to ascertain the amorphous/crystalline nature.

3. Results and discussion

3.1. Solar cell module results

Fig. 2 shows the *I–V* characteristics of an amorphous silicon cell-on foil. The intended thickness of the amorphous silicon i-layer, estimated from deposition rate of the a-Si:H layer on glass is 350 nm. This thickness is chosen to simulate the top cell of a tandem cell and to generate a current of ~13 mA/cm^2. The thickness of this i-layer in the actual cell structure, as estimated from the XTEM (Fig. 3(a)), is indeed ~350 nm (within the thickness error, considering the roughness), which is similar to the estimated value on glass. Initial *active* area (0.912 cm^2) efficiency of the cells on foil is 7.69% ($V_{oc} = 0.834$ V, FF = 0.71). A reference p–i–n cell on Asahi U-type SnO_2:F TCO with the same type of i-layer, though with 450 nm estimated thickness, gave an efficiency of ~10%. The difference in efficiency between the cell on foil and the reference cell is attributed to the smaller thickness (350 nm) and the use of a ZnO/Al back reflector instead of a ZnO/Ag back reflector. The light soaking with white light under standard conditions (50 °C for 1000 h) led to only 11% degradation in FF (Fig. 2). The open circuit voltage (V_{oc}) and short circuit current (J_{sc}) basically remain constant, as can be seen in Fig. 2. The shape of the degradation kinetics (Fig. 4) reveals that the FF degrades quickly in the initial few hours and more or less stabilizes after 100 h. This is typical for so called protocrystalline silicon materials. However, after 600 h a second stage of degradation has been observed which cannot be explained by normal Staebler–Wronski (SW) degradation behaviour of a-Si:H. We speculate that some other elements of the cell, such as the contacts, are possible causes for the degradation at this later stage (as these are not encapsulated). The minimodule showed an initial *aperture* area efficiency of 6.7%. The small difference in efficiency between the cell-on-foil and the module (considering around 8% dead area for the aperture area of a module) is attributed to the low performance of one of the series connected cells in the module. The light soaking of a similar module (Fig. 5) with an initial efficiency of 6.35% showed an efficiency of 5.15% after light soaking (at Helianthos) for 140 h. It is observed that the parallel resistance (R_p) decreases very little after ~80 h of light soaking, indicating saturation of light induced defect creation (and thus recombination) in the i-layer material. The V_{oc}, which shows a monotonic increase with light soaking also shows decay after 80 h. Further studies are in progress to understand the degradation characteristics.

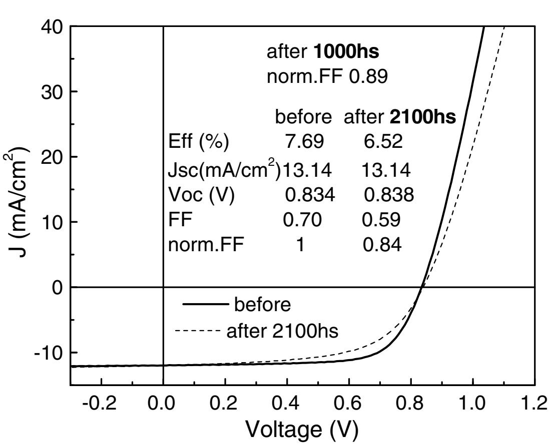

Fig. 2. *I–V* characteristics of an amorphous silicon cell-on-foil before and after 2100 h of light soaking with white light at 50 °C. The degradation of FF at 1000 h is only 11%.

In order to understand the effect of the substrate and cell structure on the structure of the materials in the solar cell, we made XTEM of the cells on foil and compared it with the cell on Asahi TCO on glass. Fig. 3 shows the XTEM images, (a) for the cell on Al/TCO and (b) for the cell on glass/Asahi TCO. Two basic observations can be made; (i) the thickness that provides information on deposition rate and (ii) structure and dependence of growth process on type of substrate. The actual thickness of the i-layer of the cell on foil (Fig. 3(a)) is estimated to be ~350 nm, that amounted to a deposition rate of ~0.2 nm/s. The second observation, related to structural evolution, is that there is a marked difference between cells on glass/TCO and Al/TCO. The image in Fig. 3(a) shows void structure in silicon; they are very local in the sharp valleys of TCO/Al. In the case of a-Si on glass/TCO, no voids could be seen. However, in many cases the void structure in Fig. 3(a) does not start from the TCO layer in the valley, rather after some incubation phase. Hence, the formation of the void structure could be of also some other origin, such as release of stress that is built up by differences in the volume expansion coefficient of the Al and silicon layers. It should be noted that the elongated void structure along the growth direction does not reach the full thickness, and this could be the reason that we still have good yield in the performance of the cells. The consequence of these void formations is that the i-layer should be thick enough if a single junction is made or a tandem structure may be advantageous to minimize the shunting probabilities.

3.2. Future prospects

A top cell limited tandem cell with a-Si:H/μc-Si:H structure made in ASTER system by VHF PECVD has already shown high 12% initial and 11.4% stabilized efficiencies on Asahi U-type SnO_2:F TCO [1]. To make these types of cells more stable, tandem cells with bottom cell structure (to take the advantage of the high stability of the μc-Si bottom cell) have been fabricated and an initial efficiency of 10.28%

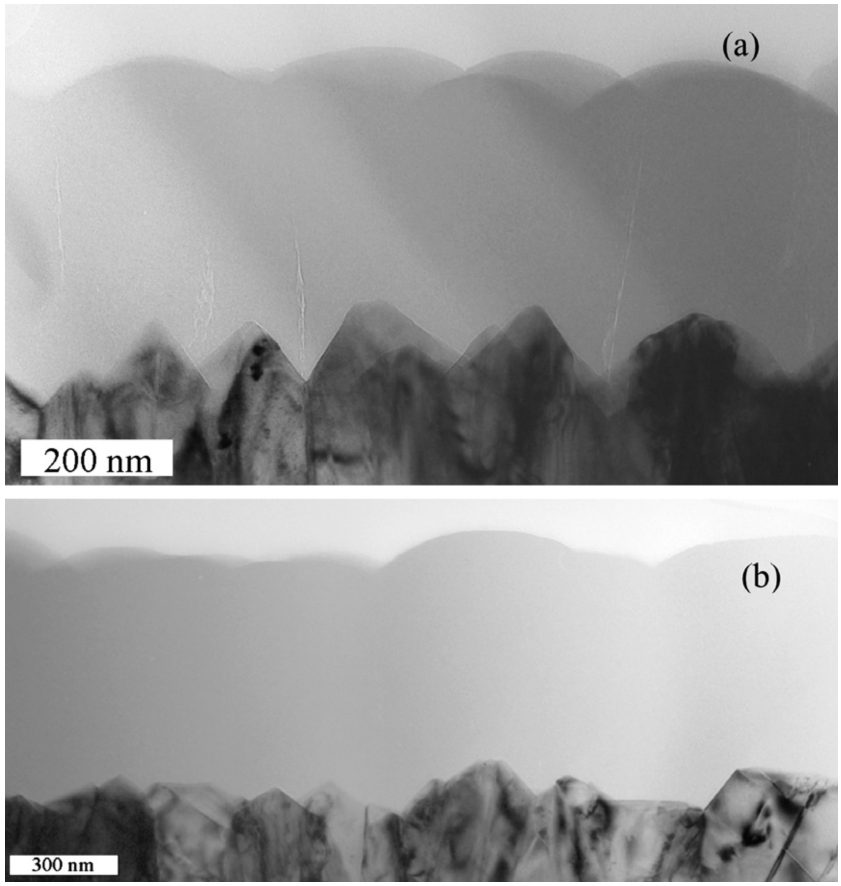

Fig. 3. XTEM images of (a) cell on Al/TCO and (b) glass/Asahi TCO.

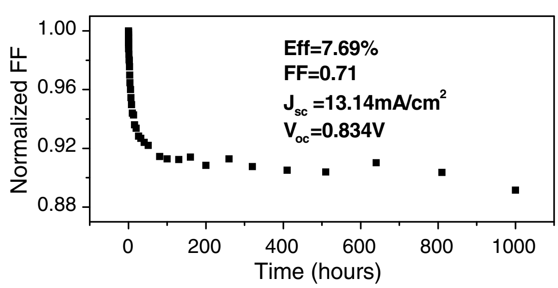

Fig. 4. Light soaking degradation behaviour of the FF of the cell-on-foil.

($V_{oc} = 1.32$ V, FF = 0.69) has been achieved. The advantage of this configuration is the shorter deposition time compared to the configuration in Ref. [1], due to the thinner bottom cell i-layer. The future course is to implement such tandem structures in the Helianthos module fabrication process. The ultimate goal is to implement the VHF PECVD process in the roll-to-roll machine and fabricate large area modules of high efficiencies. At present single junction a-Si modules by RF PECVD are routinely made at Helianthos. Such modules (30×30 cm^2) deliver an initial aperture area efficiency up to 7.2%. With the implementation of a-Si:H/μc-Si:H tandem cells, and with further developments, a stabilized efficiency of 9% will be within reach.

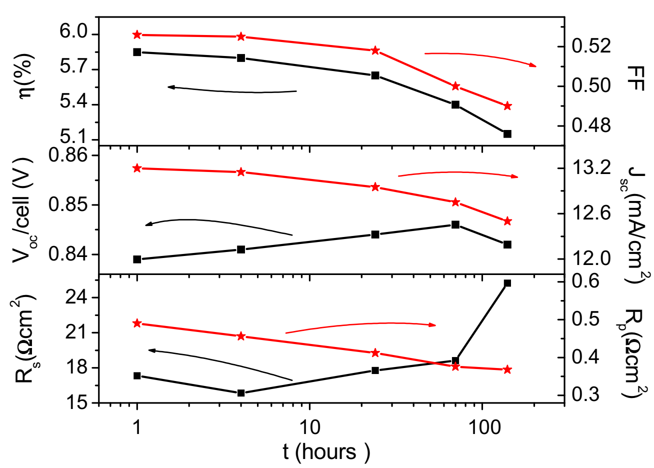

Fig. 5. Light soaking behaviour of an a-Si:H minimodule.

4. Conclusions

We have shown the fabrication of VHF PECVD deposited amorphous silicon solar cell plastic modules, made using the Helianthos concept and have studied their behaviour under light soaking. A cell on foil with initial active area (0.912 cm^2) efficiency of 7.69% ($V_{oc} = 0.834$ V, FF = 0.70) and a minimodule of 8×7.5 cm^2 with initial aperture area efficiencies of 6.7% ($V_{oc} = 6.32$ V, FF = 0.65) have been achieved. For the cell on foil a degradation of 11% of FF in 1000 h showed promising stable characteristics of amorphous cell on plastic substrates.

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