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Annealing effects in low temperature amorphous silicon flexible solar cells

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Abstract

We report the effects of prolonged post-deposition annealing on the performance of amorphous silicon (a-Si:H) solar cells and single layers, that are fabricated at low temperature of 120 °C on flexible PET and glass substrates. These low temperature solar cells show a significant improvement in performance upon post-deposition annealing (up to two hours) in all parameters of the current-voltage (JV) curves of the solar cell, resulting in an efficiency increase up to 34 % (relative). Comparison of external quantum efficiencies of p- and n-side illuminated cells, as well as varied absorber layer thicknesses and reverse bias voltage, suggest that the collection of minority carriers are mainly improved upon annealing. Both the increase of the built-in field in the solar cell and improvement in the electronic properties of the absorber layer were found to contribute to an improved carrier collection and solar cell performance.

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1. Introduction

Thermal annealing effects in amorphous silicon (a-Si:H) solar cells have been a subject of intensive studies. A significant portion refers to reduction in performance of a-Si:H solar cells under prolonged illumination, known as Staebler-Wronski-Effect (SWE) [1], and corresponding improvement in performance upon annealing. Various aspects of the annealing behaviour have been studied: degradation-annealing kinetics, variations in annealing temperatures and also times [2–6]. The light-soaking generated effects are usually reversible upon annealing. In such case, the reduction and improvement in performance are commonly related to the intrinsic absorber layer, particularly the decrease or increase in defect density, which are commonly related to hydrogen atoms and dangling bonds. The hydrogen content of amorphous silicon, which is linked to other properties like band gap and conductivity, critically depends on the deposition temperature during the plasma enhanced chemical vapour deposition (PECVD) process. Hydrogen-rich a-Si:H materials, usually obtained at lower deposition temperatures, are known to be more sensitive to prolonged illumination than layers containing less hydrogen, resulting in a higher magnitude of changes during the light-soaking-annealing cycles [7]. An advantage of amorphous silicon solar cells produced at low temperatures below 140 °C, is the suitability for use on low cost plastic films for flexible devices. These flexible devices have the advantages of being lightweight and enabling specialized applications like building integrated photovoltaics (BIPV) with a variety of shapes and sizes. However, low temperature solar cells are particularly sensitive to post-deposition annealing treatments. Brinza et al. studied a-Si:H solar cells deposited at 100 °C and showed an efficiency increase of up to 40 % due to post-deposition annealing at 100 °C, mainly due to an increase in V_{oc} [8]. Other studies reported an even stronger increase in efficiency up to a factor of 5 for a deposition temperature of 75 °C and annealing at 110 °C, caused by a strong increase in short-circuit current density [9]. An improvement of 50 % was found by Wang et al. for amorphous silicon germanium solar cells prepared at 200 °C for different annealing temperatures up to 230 °C [10].

In this work, we report on the effects of post-deposition annealing of low temperature (120 ± 10 °C) amorphous silicon solar cells, prepared on glass and transparent polyethylene terephthalate (PET) substrates. We show that all parameters of the current-voltage (JV) curves of our a-Si:H solar cells are significantly improved upon annealing at 120 °C during more than two hours, resulting in an efficiency improvement up to 34 % relative. While only slight changes were found in the electrical and optical properties of the individual layers upon annealing, a comparison of performance of p- and n-side illuminated cells with varied absorber layer thicknesses suggest that the minority carriers are largely responsible for the improvement in the performance of the solar cells by post-deposition annealing.

2. Experimental

Amorphous silicon (a-Si:H) layers and solar cells were fabricated by RF-PECVD in a UHV cluster tool deposition system using a gas mixture of silane and hydrogen. Trimethylborane and phosphine were added as doping gases for the deposition of p-type and n-type layers, respectively. The substrate temperature during the deposition was kept at a nominal temperature of 120 °C. Additionally, a standard temperature a-Si:H solar cell was prepared at a substrate temperature of 200 °C for comparison. More details on the deposition process can be found in [11]. Solar cells in p-i-n deposition sequence were prepared on commercially available Asahi-U type substrates with an absorber layer thickness of 450 nm or 150 nm. For p-side illuminated cells, the back contact is formed by evaporation of silver pads, which simultaneously define the cell area of 1 cm². Additionally, n-side illuminated cells were fabricated, where a thin layer of indium-doped tin oxide, covered with a small silver grid is used as front contact and the glass side of the Asahi-U type substrate is covered with silver to serve as back contact (see also [12] for additional details). Individual layers (a-Si:H p-, n- and i-types) with layer thickness between 350 to 500 nm were prepared on Corning Eagle XG glass substrates. Conductivities of individual layers were measured with evaporated coplanar silver contacts in vacuum. Photosensitivity *PS* for the intrinsic absorber layer is defined as the ratio of photo (σ_p) to dark (σ_d) conductivity. The solar cells were characterized using a class A sun simulator for *JV* measurements under 100 mW/cm^2 AM1.5 illumination at a temperature of 25 °C. Fill factor (*FF*), open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}) and efficiency (η) were evaluated from these JV curves. External