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Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Amorphous silicon–germanium for triple and quadruple junction thin-film silicon based solar cells



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ARTICLE INFO

Article history:

Received 25 August 2014

Received in revised form

21 October 2014

Accepted 3 November 2014

Keywords:

Thin-film Si

Silicon–germanium

Multijunctions

Alloyed materials

Light management

ABSTRACT

We study amorphous silicon–germanium (a-SiGe:H) as intrinsic absorber material for thin-film silicon-based triple and quadruple junction solar cells. First, we present the development of a-SiGe:H single junction devices, in particular the Ge-content grading in the absorber layer, the influence of the Ge-content on electrical properties and (infra)red-response, and the influence of using different types of p-layers. We subsequently show the incorporation of optimized single-junction devices in triple junction cells and discuss the interplay between Ge-content and intermediate reflector thickness. For triple junction devices with amorphous silicon (a-Si:H) top cells, a-SiGe:H middle cells and microcrystalline silicon ($\mu\text{c-Si:H}$) bottom cells, we obtained an initial efficiency of 13.6% and an efficiency of 11.3% after light-soaking. We also present a quadruple junction device with an a-Si:H top cell, a low Ge-content a-SiGe:H second cell, and $\mu\text{c-Si:H}$ third and bottom cells. In this device configuration, we obtained an open-circuit voltage as high as 2.57 V. The performance of these cells was limited by not yet optimized current matching, leading nevertheless to an initial efficiency of 10.1%. A brief roadmap towards quadruple-junction devices with stabilized efficiencies of 14% is also outlined.

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1. Introduction

Thin-film Si solar cells offer several inherent advantages compared to other photovoltaic technologies such as (i) the use of abundant and recyclable materials [1,2], (ii) the possibility to fabricate solar cells on flexible and lightweight substrates [3,4], (iii) their favorable temperature coefficient compared to standard c-Si solar cells [5], (iv) excellent esthetics for building integration thanks to homogeneous large-area module manufacturing [6,7], and (v) low energy payback times due to the low material usage and fabrication temperature [8]. Main challenges are the limited efficiency and light-induced degradation due to the Staebler–Wronski effect [9].

For single-junction thin-film Si solar cells, stabilized laboratory efficiencies exceeding 10% have been presented [10–13]. The most straightforward approach to further increase efficiency is the use of multiple junction devices, which are most commonly fabricated in the so-called tandem cell configuration using hydrogenated amorphous Si (a-Si:H) for the top cell and hydrogenated

microcrystalline Si for the bottom cell ($\mu\text{c-Si:H}$) [14–16]. For large-area ($1.1 \times 1.3 \text{ m}^2$) tandem modules, TEL Solar recently demonstrated an impressive certified stabilized efficiency of 12.24% [17].

The highest initial cell efficiency of 16.3% demonstrated so far for thin-film Si solar cells has been obtained by United Solar using a triple junction configuration [18]. In this specific case, the top cell absorber consists of a-Si:H, the middle cell absorber of hydrogenated amorphous silicon–germanium (a-SiGe:H), and the absorber of the bottom cell of $\mu\text{c-Si:H}$. The main advantage of this configuration is the use of three different band gaps for the absorber layers, enabling a very efficient use of the solar spectrum [2,18]. Moreover, by tuning the Ge/Si ratio in the a-SiGe:H absorber, the band gap of the absorber layers can easily be adjusted. The excellent cell and module results by United Solar were all obtained in n–i–p configuration. With the same stack of component cells, LG Electronics very recently presented large-area thin-film Si modules with a stabilized efficiency of 11.2% in p–i–n configuration [19]. The main challenge of triple cells including a-SiGe:H component cells lies in the strong light-induced degradation of this material. For this reason, the highest efficiencies after light-soaking (1000 h) have so far been obtained with a-Si:H top cells and $\mu\text{c-Si:H}$ middle and bottom cells [20–23]. For this cell configuration, however, relatively thick devices are necessary

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compared to the configuration including a-SiGe:H middle cell absorbers [24].

In this study, a-SiGe:H as absorber layer material for thin-film Si triple and quadruple junction solar cells [25,26] in p-i-n configuration is investigated. Contrary to previous work in the literature, we present in detail the fabrication and development of single-junction a-SiGe:H devices, followed by their incorporation in triple junction cells. We present the optimization of the p-layer structure, show the necessity of intrinsic a-Si:H buffer layers at the p/i and i/n interfaces as well as the use of graded absorber layers, and finally show cell results for varying absorber band gap values. We use these component cells in triple junction devices and assess the influence of Ge-content and intermediate reflector layer (IRL) thickness on cell performance and stability. Finally we show first experimental quadruple-junction devices with a low Ge-content a-SiGe:H second cell (seen from the glass side).

2. Experimental details

All a-SiGe:H layers and corresponding single-junction devices were fabricated in an Octopus I cluster tool developed by Indeotec SA [27,28]. The a-SiGe:H films were deposited by very high frequency plasma-enhanced chemical vapor deposition (VHF PECVD) at a plasma excitation frequency of 40.68 MHz on a small area ($15 \times 16 \text{ cm}^2$) from a gas mixture of SiH_4 , GeH_4 , and H_2 . The absorber layers have a thickness of approximately 220 nm. The p-type layer stack of a-SiGe:H-based cells consists of a p-($\mu\text{-SiO}_x\text{:H}$) film [29] and either a p-(a-Si:H) or a p-(a-SiC:H) film. The n-type layer stack consists of an n-(a-Si:H) film and an n-($\mu\text{-SiO}_x\text{:H}$) film that also acts as an IRL when incorporated in triple junction devices.

For triple-junction devices, the a-Si:H based top cells were deposited in a small-area home-made system as described in Ref. [23]. The intrinsic absorber layer thickness of the top cells is approximately 130 nm and the Tauc–Lorentz band gap is around 1.7 eV as measured by spectroscopic ellipsometry. The $\mu\text{-Si:H}$ -based bottom cells have a 2.6- μm -thick absorber layer, deposited in a medium-sized ($50 \times 60 \text{ cm}^2$) R&D KAI-M reactor [30]. These bottom cells contain a $\mu\text{-SiO}_x\text{:H}$ buffer layer at the p/i interface [23,31]. The $\mu\text{-Si:H}$ absorber layers were fabricated using advanced hydrogen profiling to accurately tune the crystallinity during cell deposition [11,32,33].

The presented quadruple-junction device consists of a 110 nm a-Si:H top cell, a low-Ge-content 220-nm-thick a-SiGe:H second cell and a 1.7- μm -thick $\mu\text{-Si:H}$ third cell [34], all deposited in the Octopus I system. The bottom cell structure of the quadruple-junction device is the same as the one used for the triple-junction devices studied in this work. The bottom cell absorber layer has been deposited at a higher hydrogen dilution than the third cell, leading to an enhanced crystallinity.

All devices were fabricated in p-i-n configuration on $4.1 \times 4.1 \text{ cm}^2$ Schott AF 32 front glass with a thickness of $(0.5 \pm 0.05) \text{ mm}$, cleaned in acidic/basic baths prior to cell fabrication. Boron-doped ZnO front and back electrodes were made by low-pressure chemical vapor deposition (LPCVD) in a home-made system from a gas mixture of diethyl-zinc (DEZ) and water [35]. Diborane (B_2H_6) was added as dopant gas. The rough ZnO front electrodes were slightly smoothed using an Ar plasma [36]. We used the same front and back electrodes as described in Ref. [23]. Individual cells were subsequently patterned by lift-off and plasma dry-etching. For single-junction a-SiGe:H devices, each sample consists of 16 cells with an area of 0.25 cm^2 , whereas for the triple and quadruple junction devices, each sample consists of six cells with an area of 1.05 cm^2 .

Finally, the cells were characterized by means of current density versus voltage (J - V) and external quantum efficiency

(EQE) measurements. J - V measurements were performed under AM1.5G illumination (1000 W/m^2) using a class AAA solar simulator [37]. EQE measurements were performed in the wavelength range between 370 and 1100 nm with a step size of 10 nm under appropriate bias light and voltage conditions [21,23] to determine the current densities of the individual subcells. Light-soaking was performed for 1000 h at $(50 \pm 5) ^\circ\text{C}$.

3. Results and discussion

3.1. a-SiGe:H single-junction solar cells

When starting our work on a-SiGe:H, we decided to use similar deposition conditions (pressure, power density, temperature) as for low-pressure a-Si:H [23,27]. In particular, we applied a low Ge content ($\text{GeH}_4/\text{SiH}_4$ flow ratio=5%) leading to a Tauc–Lorentz gap of 1.60 eV for the used conditions, and used the same doped layers as for a-Si:H cells [27]. Thin intrinsic (10 nm) a-Si:H buffer layers were applied at both interfaces (i/p and i/n) to reduce defect formation at these interfaces [38]. With this device configuration, we managed in quite a straightforward manner to fabricate a cell with an open circuit voltage (V_{OC}) of 824 mV, a fill factor (FF) of 58.0%, a short-circuit current density (J_{SC}) of 16.9 mA/cm^2 , leading to an initial efficiency of 8.1%. This cell was measured with a white back reflector, and without an anti-reflective coating on the front side.

Several laboratories [2,39,40] have demonstrated the advantages of using a graded Ge-profile in the a-SiGe:H absorber layer to facilitate charge transport by avoiding too abrupt band offsets. We also implemented such a grading in our fabrication process. We used a similar grading profile as proposed by United Solar, which is V-shaped and has its steepest slope as well as the lowest band gap near the p/i interface [2]. In our case, incorporating a graded intrinsic a-SiGe:H absorber layer led to an increase in FF by 3% absolute. An even stronger increase in FF was obtained by modifying the p-type layer stack. The reference p-layer stack consists of a $\mu\text{-SiO}_x\text{:H}$ p-layer and an a-SiC:H p-layer. As said before, we started with the same doped layers as for standard a-Si:H cells [27]. In such cells, an a-SiC:H p-layer shows excellent window layer properties due to its high band gap and therefore the devices show a high response in the blue part of the solar spectrum. In a-SiGe:H cells, however, the band offset between the a-SiGe:H film and the a-SiC:H p-layer could be too severe and therefore hinder charge transport [22]. Furthermore, parasitic absorption by the p-layer in the blue part of the spectrum is less critical for the second component cell than for the top cell. Hence, we fabricated four different single-junction a-SiGe:H cells, in which only the amorphous p-layer was varied: the first one is the reference layer (i.e. a-SiC:H), the second one is the same layer as the reference, but with half its thickness, the third one is a standard a-Si:H p-layer and the fourth cell was deposited without any amorphous p-layer. The corresponding cell results (V_{OC} , FF, J_{SC} and efficiency) are shown in Table 1. In Fig. 1, the EQE curves of these cells are shown.

The data in Table 1 show that replacing the a-SiC:H layer by an a-Si:H p-layer leads to a considerable increase in V_{OC} and FF. Even reducing its full thickness (~ 6 – 7 nm) to half its original value already leads to a strong increase in FF, most likely due to that fact that in this case holes can tunnel more easily through the wide gap a-SiC:H film. Fabricating the cell without any amorphous p-layer also leads to a considerable FF increase, but in this case the V_{OC} is strongly reduced. From Fig. 1, a significantly reduced blue response can be observed when replacing the a-SiC:H p-layer by a p-type a-Si:H film. However, the use of a transparent window layer is less important for these cells, as they will finally be employed as

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