Solar Energy Materials & Solar Cells 140 (2015) 344–350

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Nano-textured superstrates for thin film silicon solar cells: Status and industrial challenges

J.-B. Orhan [a], R. Monnard [a], E. Vallat-Sauvain [a,*], L. Fesquet [a], D. Romang [a], X. Multone [a], J.-F. Boucher [a], J. Steinhauser [a], D. Dominé [a], J.-P. Cardoso [a], D. Borrello [a], G. Charitat [a], B. Dehbozorgi [a], G. Choong [a], M. Charrière [a], S. Benagli [a], J. Meier [a], J. Bailat [b], J. Escarré [b], N. Blondiaux [b], J. Sakurai [c], J. Lin [c], A. Matsunaga [c], P. Losio [d]

[a] TEL Solar-Lab, rue du Puits Godet 12a, CH-2000 Neuchâtel, Switzerland
[b] CSEM, Rue Jaquet-Droz, 2002 Neuchâtel, Switzerland
[c] TEL Technology Center Tsukuba, 17 Miyukigaoka, Tsukuba City, Ibaraki Prefecture, Japan
[d] TEL Solar AG, Hauptstrasse 1a, 9477 Trubbach, Switzerland

ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form
13 April 2015
Accepted 16 April 2015

Keywords:
Micromorph
Amorphous silicon
Microcrystalline silicon
Nanoimprint
Light scattering

ABSTRACT

Thin film tandem solar cells based on amorphous and microcrystalline silicon (Micromorph™ in superstrate configuration) benefit from strongly light-scattering nano-textured substrates. A development methodology for the evaluation of the performance of the Micromorph test cells deposited on such substrates with very different surface shapes is presented and illustrated. It is shown that growth related defects and non-conformal coverage of the silicon layers restrict the choice of surface shapes for this photovoltaic application. General guidelines are given in this study for the preferred selection of the surface geometry for Micromorph™ test cells. The results indicate that the application of advanced surface shapes for higher conversion efficiencies requires improved silicon deposition process compared to current industrial state-of-the-art.

1. Introduction

Since the early developments of thin film silicon solar cells a notable gain in conversion efficiency has been obtained by using tandem silicon-based sub-cells comprising an amorphous silicon (a-Si:H) top cell, absorbing efficiently the high-energy component of the solar spectra, with a microcrystalline silicon (μc-Si:H) bottom cell, absorbing the remaining low-energy component of the spectra [1,2]. Such tandem devices are called "Micromorph". In industrial application of the Micromorph™ device the total silicon thickness amounts 1–2 μm, very thin in comparison with the hundred to two hundred micrometers of silicon used in the crystalline (c-Si) device counterpart [3]. The thin film device design industrially applied results in rather low total photocurrents (below 30 mA/cm^2) compared to the c-Si devices (well above 30 mA/cm^2). Therefore, a strong effort is being devoted to the design and development of light harvesting schemes in Micromorph™ solar cells. This effort has been rewarded with very high photocurrents on dedicated transparent rough substrates using for example the combination of flat glass coated with rough as-grown Transparent Conductive Oxides (TCO). This solution is the current industrial standard. More advanced technologies applying "roughening"/texturation processes to the optical interfaces underlying the silicon layers have been proposed. In particular, the nano-texturation of an additional polymeric layer applied onto the flat glass [4–8] is of industrial interest.

In this contribution we detail the experimental results obtained in Micromorph™ test cells deposited on two classes of strongly scattering substrates used in the superstrate configuration: advanced surface shapes are obtained by inserting a Nano-Imprinted (NI) transparent polymeric layer in-between the Flat Glass (FG) and the transparent conductive layer consisting of zinc oxide (ZnO) needed as front contact of the device (this substrate configuration is denominated here NI-G/ZnO). These results are compared with those obtained by using a standard flat glass coated with different as-grown ZnO layers (such substrates are denominated here FG/ZnO). A new characteristic feature for the surface shape of FG/ZnO substrates is introduced and shown to impact negatively the open-circuit voltage. Then, the local silicon thickness distribution is quantified for selected substrates of the NI-G/ZnO and of the FG/ZnO classes. The effects of the local thickness distribution on the electrical performances of the device are discussed. Finally, the sensitivity of the

* Corresponding author. Tel.: +41 32 724 12 14.
E-mail address: evelyne.vallat@gmail.com (E. Vallat-Sauvain).

http://dx.doi.org/10.1016/j.solmat.2015.04.027
0927-0248/

microcrystalline silicon layer quality on the substrate surface shape is qualitatively illustrated for three typical Plasma Enhanced Chemical Vapor Deposition (PECVD) conditions.

2. Material and methods

2.1. Substrates fabrication

Thin film silicon Micromorph™ are p–i–n devices fabricated in the so-called "superstrate" configuration, i.e. the light impinges the device from the glass side. In this study, we call "substrates" the transparent structure underlying the silicon. The flat substrates used here are $50 \times 50 \times 1$ mm^3 borosilicate glasses. For comparison purposes, the references consist of FG coated with the industrially relevant LPCVD ZnO front electrode [10]. The deposition conditions of the other various LPCVD-ZnO layers are based on previous developments as described in [9]. The second set of substrates investigated consists of nano-imprinted glasses subsequently coated with a thin ZnO layer. With this approach a large variety of NI-G surface shapes [11] has been evaluated according to the screening methodology described below. The technology for the fabrication of NI shapes is based on the replication of a master texture into a resin layer deposited on the flat glass substrates [12]. Our masters were developed internally using various techniques, like accurate microfabrication processes and taking advantage of the natural growth of specific materials like LPCVD ZnO. Masters are replicated in a so-called working mold. Transparent polymeric material coated with an anti-adhesive layer is used for the replication step. This working mold is subsequently used for the embossing of a resin deposited by spin or slit coating on our FG substrates. Proper UV curing and thermal treatment are finally applied. All our nano-imprint steps are industrially scalable to substrate size of Gen5 [11].

2.2. Substrate characterization

The NI-G/ZnO surface and FG/ZnO surfaces were statistically characterized from AFM topography scans obtained with a Nanosurf Easyscan 2 microscope. Scanned areas were typically 5×5 μm^2 on as-grown ZnO and up to 40×40 μm^2 on NI-G/ZnO. The statistical surface analysis includes evaluation of the average roughness (Ra), root mean square roughness (RMS) and radial autocorrelation length (T). These values were obtained with specific modules of the Gwyddion software [13]. As introduced earlier by Nasuno et al. [14] an average half-opening angle (beta) of the faceted surface features can be evaluated from the values of Ra and T with the relationship beta=arctg (T/(4Ra)). A new characteristic figure related to the occurrence of growth-related porous zones in the material ("cracks" as defined in [15]) is introduced here: the fraction of Rare High Pyramids (RHP). This parameter is obtained by counting all local features protruding out of the lowest plane of the layer with the watershed algorithm available in [13] as represented in Fig. 1a. Then all features out-standing 80% above the median height of the sample are counted (Fig. 1b). The ratio of these two values yields the unitless RHP percentage value, introduced here to characterize critical as grown LPCVD ZnO textures.

The substrates are further optically characterized by measuring-the total (TT) and diffuse (DT) optical transmittance in air with a double beam Perkin–Elmer lambda-950 photo-spectrometer equipped with an integrating sphere. The haze is then calculated from the value of the ratio DT/TT at 600 nm (ratio of the diffused over total transmittance). The larger this value is, the stronger is the light-scattering capabilities of the substrate in air. For the substrate description in the text the last two digits express the value in [%] of their optical haze: for example a flat glass coated with as-grown ZnO of 10% haze at 600 nm will read FG/ZnO 10 (see Table 1).

2.3. Fabrication of Micromorph™ solar cells

In order to evaluate the potential benefits of various NI-G substrates on the test cells efficiency, Micromorph™ devices are co-deposited in successive runs with nominally the same deposition processes. A controlled reference base-line is obtained in every run by using the industrial-like FG/ZnO 40 substrate. Thin film silicon sub-cells for Micromorph™ tandem consist of continuously optimized state-of-the-art top a-Si:H cells [16] deposited

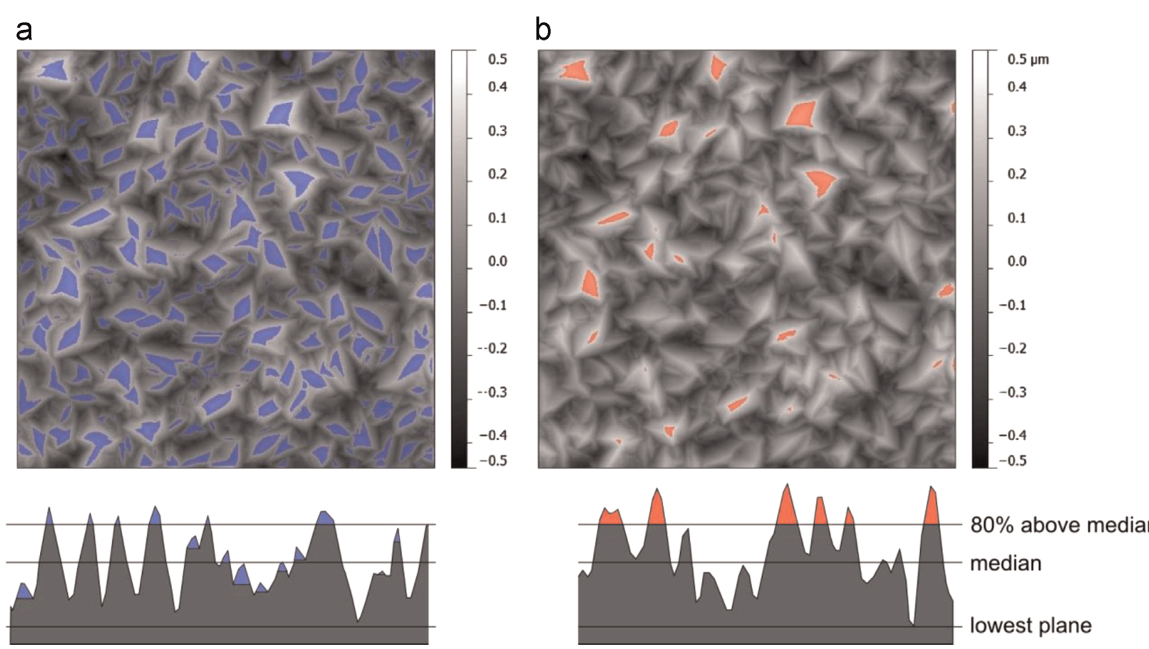

Fig. 1. AFM topography scans (10×10 μm^2) of as-grown LPCVD ZnO 20 with (a) all the pyramids marked in blue with a watershed algorithm [13] and (b) only the highest (z-values larger than 80% of median) protruding pyramids (marked in red). The threshold value does not influence our interpretation when it is chosen between 70% and 90%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)