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Advanced light trapping designs for high efficiency thin film silicon solar cells

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ABSTRACT

State-of-the-art optical trapping designs for tandem thin film silicon solar cells in the superstrate configuration commonly feature two elements: a textured transparent conductive oxide front contact and a low refractive index interlayer between top and bottom cell. We investigate more advanced super light trapping schemes that have been designed and implemented in thin film tandem junctions at different levels in the solar cells to further enhance light trapping capabilities. Regularly patterned nano-imprinted substrates offer an additional capability to tune the substrate morphology and optimize it for enhanced solar cell performance. We show that the onset of defect formation in thin film layers can be controlled and that the spectral response in the infra-red part of the spectrum is increased. Intermediate reflectors with ultra-low refractive indeces and plasmonic properties lead to increased light confinement in top cells. Results show that reducing the refractive index below 1.5 still leads to a substantial current increase in the top cell. These innovative designs improve the output current in amorphous/microcrystalline tandem devices with thin photo-active layers. In addition, they surprisingly enhance the electrical parameters of the tandem cells with a record open circuit voltage of 1.47 V. Plasmonic effects of metal nano-particles embedded in interlayers do not compromise the electrical solar cell parameters and similarly strengthen light confinement in the top cell, however detrimental effects are observed in the bottom cell current output.

1. Introduction

Kaneka has a long history in thin film microcrystalline (μc-Si:H) single junction, amorphous silicon/microcrystalline silicon (a-Si:H/μc-Si:H) tandem junction and a-Si:H/interlayer/μc-Si:H stacked solar cell research [1–3]. These efforts were also based on the pioneering work done by Hamakawa et al. in 1983 in the domain of thin film silicon materials and solar cell devices [4]. Another breakthrough came with the report by Meier et al. of the University of Neuchâtel about a 7% efficient μc-Si:H single junction solar cell and a 13% initial efficiency for a-Si:H/μc-Si:H tandem cell in 1996 [5]. In the following year, significant progress was made in thin film μc-Si:H solar cell on glass substrate fabricated by plasma enhanced chemical vapor deposition (PECVD) at low temperature: the cell efficiency of a single-junction μc-Si:H cell by Kaneka Corporation exceeded 10% [6]. The last decade has continued to witness significant research and industrial developments in this area: Kaneka has developed thin film tandem solar cells and improved solar cell designs with a transparent interlayer between a-Si:H top cell and μc-Si:H bottom cell to enhance internal light trapping [7,8]. A record initial aperture efficiency of 13.4% for a tandem thin film silicon HYBRID PLUS module (size: $910 \times 455\ mm^2$) was achieved [9–12].

Recently, the focus in thin film silicon technology has gradually shifted away from single junction amorphous silicon and intensified on tandem devices. In particular there has been a trend to: (1) extend the light scattering capabilities of TCOs from the visible spectrum (suitable for a-Si:H) to the near infra-red to increase the light confinement in the uc-Si:H bottom cell; and (2) reduce the refractive index of intermediate reflectors to confine more light in the a-Si:H top cell and reduce parasitic absorption.

In today's state-of-the-art transparent conductive oxides (TCOs), light trapping is commonly introduced by developing a rough (or textured) surface morphology during the TCO growth process: light is scattered to angles different from normal incidence at the rough interface between TCO and silicon, because of the refractive index mismatch between the two materials. This

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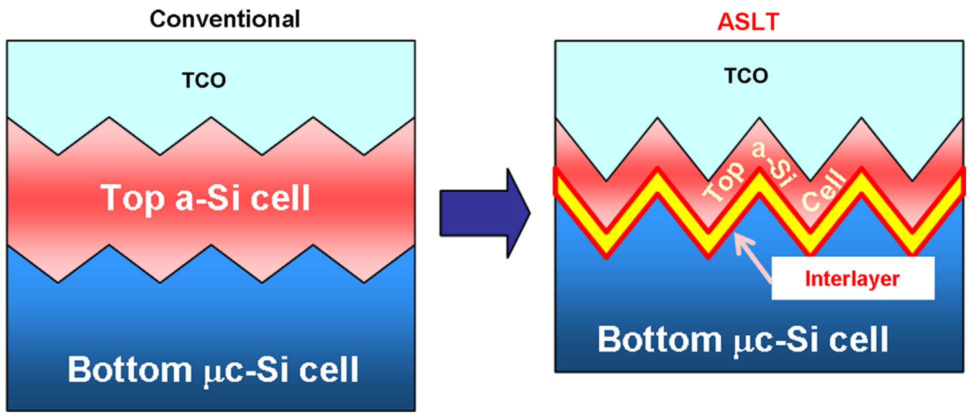

Fig. 1. A comparison of the conceptual structures for a conventional cell and an ASLT cell.

effect increases the light path and absorption in silicon leading to higher output currents. The approach has been applied successfully in thin film silicon technology in both substrate and superstrate configurations. The most widespread TCOs used for this purpose are SnO2 or ZnO that spontaneously develop rough surfaces during chemical vapor deposition [13–15]. Alternatively ZnO can be sputtered and chemically textured after deposition [16]. A common way to characterize these TCO substrates is by means of the scalar scattering theory where the substrate morphology is described using a single statistical parameter for the roughness [17,18].

Different approaches have been followed to improve this baseline and are collectively denominated multiscale TCOs, indicating the fact that more than one parameter is needed to characterize the morphology of the surface: examples are the modified growth of SnO2 to realize small texture superimposed on large texture features [19]; texturing the glass substrate [20]; using nano-imprinting technology to pattern a transparent sol–gel material on a glass substrate [21,22].

In the case of interlayers, it is the combination of refractive index and layer thickness (or equivalently, the optical length) that achieves the desired effect of partially reflecting back light in the top cell, increasing light trapping and current output. State-of-the-art interlayers are also based on TCOs or alternatively on conductive SiO_x layers [23]. Confinement in the top cell can be tuned with the thickness of the interlayer, but since absorption losses in interlayers are difficult to eliminate and thick layers introduce optical resonance effects [24], best results are typically obtained using thin layers with as low as possible refractive index. Therefore the development of conductive materials with extremely low refractive index represents a realistic way to improve the light trapping capabilities beyond today's baseline.

Using a different approach, it has been argued that the introduction of metal nano-particles has the potential to increase the short circuit current of thin film silicon devices. Depending on the particular application and the wavelength range, optimum positions within the solar cell structure have been identified. Especially the insertion of metal nano-particles at the rear side of the solar cell is considered a promising route for higher efficiency because it avoids unwanted back-scattering processes and parasitic absorptions. Reports have indeed shown that it is possible to increase the short circuit current of amorphous single junction solar cells by embedding metal nano-particles in the back reflector. However, the baseline is often set to a flat reflector and the actual gain over standard high efficiency device structures (silicon growth on textured TCO) is not always clear [25,26]. We do not yet observe improvements over the state-of-the-art baseline when inserting metal nano-particles in back reflectors, however we were able to show an enhancement effect in interlayers [27].

To harness these innovative ideas and to advance the technologies for internal light trapping, Kaneka has been proposing and developing the "Advanced Super Light Trapping (ASLT)" structure for thin film silicon solar cells. The ASLT concept contains three new technologies (see Fig. 1): (1) designed TCO features; and (2) very thin a-Si:H layer for top cell; and (3) advanced super interlayer (ASI).

With the term "designed TCO feature" we intend a TCO morphology (and a method to control such a morphology) that has the capability to optically manipulate a certain wavelength range for the enhancement of the photo-current generation. The purpose of the design is to obtain an effective light trapping for: (1) the μc-Si:H bottom cell which has a low absorption coefficient; and (2) the a-Si:H top cell by selective wavelength reflection from the interference between TCO and interlayer. This concept can therefore make both a-Si:H top cell and μc-Si:H bottom cell much thinner and increase throughput. The precise control of ASLT structures has not only produced an enhancement of the short-circuit current density, but also a remarkable improvement in open-circuit voltage. Consequently the performance of a-Si:H/μc-Si:H tandem solar cells was improved.

2. Experimental

The details of the processes and characterization techniques used in the different ASLT implementations will be described and discussed in the following relevant sections of this paper. In this paragraph, only the process steps common to all different approaches are outlined.

Thin film silicon solar cells were grown in superstrate configuration on commercially available glass/TCO substrates. ZnO was deposited by standard low pressure chemical vapor deposition and was doped with boron. The silicon layers were deposited by PECVD using hydrogen silane mixtures for the intrinsic layers and adding p and n dopant gases to form the doped layers at temperatures around 200 C. The back reflectors for single junction and tandem cells were obtained by standard sputtering of aluminum doped ZnO and Ag layers.

3. Results

3.1. Designed TCO feature

We used nano-imprinting as a method to control the surface morphology of TCO layers. Fig. 2 shows a cross-sectional sketch of