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Micromorph silicon solar cell optical performance: Influence of intermediate reflector and front electrode surface texture

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ABSTRACT

The optical performance of tandem a-Si:H/μc-Si:H (micromorph) thin film solar cell was investigated experimentally and by means of rigorous 3-D optical simulation. The interplay of intermediate reflectors, with different refractive indices and thicknesses, and front electrode surface texture was studied. Experiments and simulations show that LPCVD ZnO based front electrodes have the highest optical potential together with a low refractive index of the intermediate reflector. The intermediate reflector layer serves for redistribution of the mid-range solar spectrum between the top and bottom cell, while the sum of the top and bottom cell currents decreases with increasing IRL thickness. Additionally, promising concepts to increase the short-circuit current of the tandem solar cell are shown. The most important steps are related to lowering parasitic absorption in supportive layers by the introduction of silicon oxide layers and improving the light incoupling by introduction of anti-reflective layers.

1. Introduction

Thin-film silicon (TF-Si) photovoltaic devices exhibit many advantages: Due to their thickness in the range from only 200 nm up to a few micrometers the material and energy consumption is low which also keeps the fabrication costs low. However, the conversion efficiency needs to be further improved to be competitive with crystalline silicon solar cells. The highest efficiencies among laboratory TF-Si solar cells have been achieved with a triple junction solar cell combining a hydrogenated amorphous silicon top cell with hydrogenated microcrystalline silicon middle and bottom cells (a-Si:H/μc-Si:H/μc-Si:H), or with tandem a-Si:H/μc-Si:H (micromorph) solar cells [1]. To mitigate the degradation of the a-Si:H top cell due to the Staebler–Wronski effect, it needs to be as thin as possible [2]. However, a thinner a-Si:H cell is prone to shunts (reduction of fill-factor) and causes a decrease of the short-circuit current J_{SC_top}, which results in a top-cell-current-limited device. This phenomenon is much more relevant in tandem micromorph Si solar cells than in the triple configuration and can be circumvented by an intermediate reflector layer (IRL) of a refractive index lower than that of Si, integrated between the top and the bottom cell [3]. An IRL reflects back part of the light that is not absorbed during its first passage through the top a-Si:H cell, thus, enabling a reduction of the a-Si:H solar cell thickness, while keeping its short-circuit current density matched with the one of the bottom cell. Several research groups have been pursuing towards the optimized tandem structure with IRL [4–10]. Merging the experimental results in the frame of the European project Fast Track revealed that the effectiveness of an IRL is not only determined by its refractive index (n) [5] and thickness (d) [8], but is a complex interplay of these two properties together with the interface texture, which results from the superstrate/substrate texture and the non-conformal growth of TF-Si layers [11].

In this paper we focus on IRLs based on mixed-phase hydrogenated amorphous/microcrystalline silicon oxides (μc-SiO$_x$), which are electrically appropriate candidates for IRLs that offer adjustable optical properties [6]. All silicon-oxide based IRLs will be denoted as SOIRL. We have studied SOIRL effects both experimentally as well as by using rigorous 3-D optical simulations. Furthermore, promising concepts to increase the short circuit current of micromorph tandem cells have been evaluated.

2. Experimental

In order to analyze the interplay of the substrate roughness, the refractive index and thickness of SOIRL and the thickness of a-Si:H

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and μc-Si:H cells in tandem configuration we have conducted experiments at three different institutes: Ecole Polytechnique Federale de Lausanne (EPFL), Forschungszentrum Jülich (FZJ) and Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), while rigorous simulations were performed at the University of Ljubljana. The variety of configurations for the superstrate, the top and bottom cell, the SOIRL and the back contact used in the performed experiments is shown in Fig. 1. Three different state-of-the-art superstrates were used at the three institutes to fabricate solar cells on top of it, using their own standard cell procedure.

Fig. 2 shows SEM images of the three different superstrates with three different surface morphologies that were used: single-scale sputter-etched ZnO (s-SPE) and multi-scale sputter-etched ZnO (m-SPE) [12] and low-pressure chemical vapor deposited (LPCVD) ZnO (Z2.5) [13]. The s-SPE consists of a thin ($\sim$1 μm) ZnO:Al-layer sputtered on Corning-glass. Afterwards this layer is etched at room temperature for 30 s in an HCl solution (0.5%) to create a surface-texture consisting of adjacent craters with diameters in the 0.5 to 2 μm-range (left in Fig. 2). In case of m-SPE an additional HF-etch (1%) for 10 s of the ZnO:Al surface was performed subsequently that creates steep etch-pits in sub-μm-size (middle in Fig. 2). Alternatively, natively textured ZnO:B was grown by LPCVD on glass. Optimized deposition conditions for micromorph cells were used (2.3- to 2.5-μm-thick layers with low boron doping, labelled Z2.5) treated with a slightly smoothening argon plasma after deposition [13].

Based on atomic force microscope (AFM) scans the autocorrelation length (*ACL*), which gives information about the lateral dimension of surface features (grains or valleys), and vertical root mean square roughness (σ_{rms}) [14] were calculated for all three substrates. The *ACL* for s-SPE and m-SPE were 715 nm and 630 nm, respectively, which is much higher compared to 240 nm for Z2.5. The σ_{rms} values are closer to each other (110 nm, 125 nm and 100 nm for s-SPE, m-SPE and Z2.5, respectively).

TF-Si and SOIRL were fabricated by plasma enhanced chemical vapor deposition using standard process gases (SiH3, H2, CH2, CO2, B2H6, B(CH3)3, PH3) at standard excitation frequency of 13.56 MHz (if not stated otherwise). At Jülich a 30 × 30 cm^2 reactor with a showerhead was used wherein four 10 × 10 cm^2 samples were prepared in one run. More details of the PECVD at FZJ processing can be found in [15,16]. At EPFL, cells were fabricated in an Octopus I PECVD system from INDEOtec. The doped layers and SOIRL were made at 40.68 MHz, more details are available in [17]. At ENEA SOIRLs and devices were fabricated in a lab-scale PECVD/VHF-PECVD cluster tool (MVSystems Inc.). The intrinsic layers were grown at 100 MHz. Details on the preparation of SOIRL can be found in [9,18].

Each institute made a series of the tandem solar cells with different thicknesses of their SOIRL: 40 nm, 70 nm and 100 nm

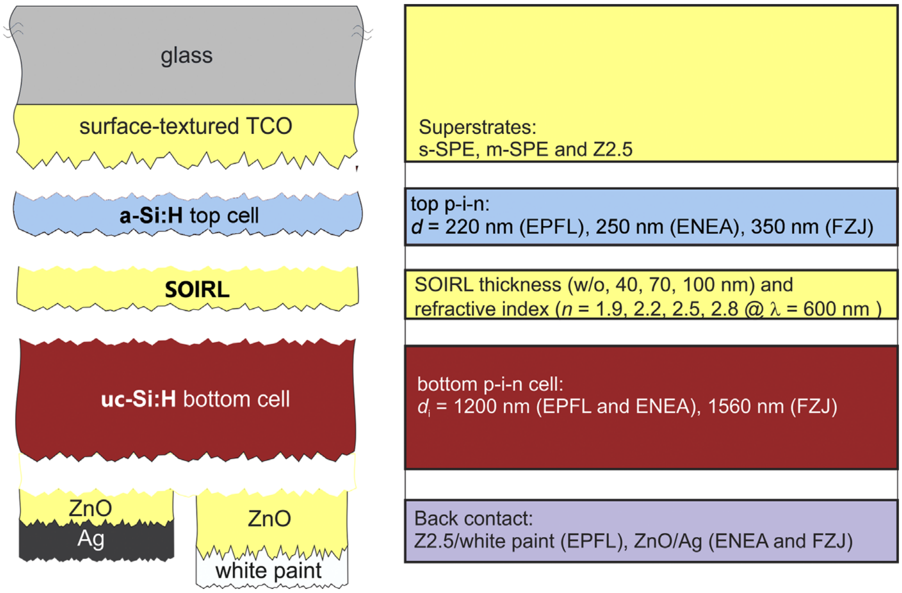

Fig. 1. Schematic drawing (left) and details (right) of the solar cell structures under test.

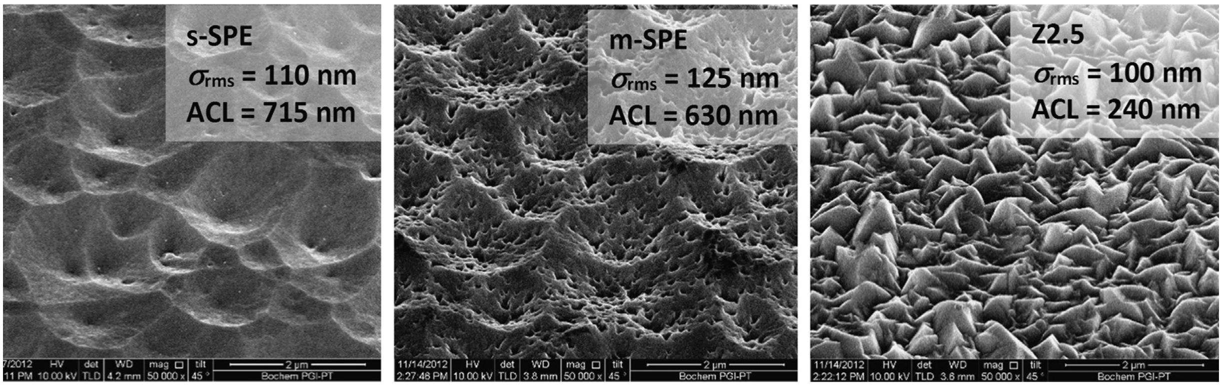

Fig. 2. SEM images of the surface morphologies of s-SPE, m-SPE and LPCVD ZnO (Z2.5) on glass, with the corresponding σ_{rms} and *ACL* values.