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Light management in large area thin-film silicon solar modules

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ABSTRACT

Light management is fundamental for achieving high performance thin-film silicon solar cells. We highlight important developments of light management for record modules subdivided into several main categories: (a) reduction of reflection at interfaces by introducing antireflective layers; (b) reduction of parasitic losses in transparent conductive oxide layers; (c) improvement of light scattering combined with transparent conductive oxide surface morphology optimization; and (d) balancing of top cell and bottom cell currents by reflective layers. Specific aspects related to industrial production of large area modules are discussed including transparency/conductivity trade-offs, optimized deposition rates and coating uniformities.

1. Introduction

Thin-film silicon solar cells based on tandem amorphous and microcrystalline silicon solar cells [1–4] offer a unique combination of band gaps for absorbing a wide range of the solar spectrum [5]. However, the comparatively low absorption coefficient in these materials combined with a total absorber thickness of only a few micrometers requires to use light management techniques to improve the efficiency [4,6]. As an additional benefit in an industrial context, light management allows to further limit the total absorber thickness thus reducing the production costs of modules [7]. For these reasons light management aspects were considered from the beginning of the MICROMORPH™ technology development. Light management begins with the glass superstrate that is optimized for transmission and mechanical robustness [8–9]. The choice of LPCVD ZnO as front and back electrode allows flexible tuning of the layer properties according to the requirements of front or back contacts combined with high transparency and low production costs [10–13]. Finally, a white lamination foil simultaneously provides broadband scattered reflection of light and encapsulation to protect the solar cell from environmental influences [14–15].

Light management was identified as one of the main factors to be optimized to reach world record performance MICROMORPH™ modules. Separate publications highlight all improvements to the module production technology to this end [16–17]. This paper will concentrate on the main paths followed at TEL Solar to improve light management, finally leading to an improved short circuit current in record modules. The following aspects were considered: (a) reduction of reflection at interfaces by introducing antireflective layers; (b) reduction of parasitic losses in transparent conductive oxide layers; (c) improvement of light scattering by transparent conductive oxide surface morphology optimization; and (d) balancing of top cell and bottom cell currents by reflective layers.

Reduction of reflections at the air/glass interface and at the glass/TCO interface by introduction of antireflective coatings (ARC) can lead to significant gains of short circuit current [18–20]. A simple estimation of the reflection losses can be made using Fresnel equations for reflection intensity at interfaces [21]. Considering approximate refractive indices at 500 nm for glass and ZnO of 1.5 and 2.0, respectively, losses due to reflection can be estimated at approximately 4% and 2%, respectively. In the following discussion the air/glass ARC will be denominated external ARC (eARC) and the glass/ZnO ARC will be denominated internal ARC (iARC). The 'rough' interface of ZnO/a-Si:H was considered to be of minor importance for light reflection due to the smooth intermixing of ZnO pyramids with a-Si:H leading to a grading of the effective refractive index. However further studies on this topic may be necessary.

The eARC in particular requires reliable processes and materials suitable for outdoor applications [22]. Additionally, the eARC should reduce reflection over the entire wavelength spectrum

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relevant for solar cells (350–1100 nm) and over a wide range of angles of incidence to optimize the energy yield of PV modules. Often eARC are prepared by sputtering or by sol–gel techniques to obtain a porous silica layer combining the required effective refractive index at 500 nm of approximately 1.3 with sufficient durability. Alternatively, graded-index coatings are used to avoid an abrupt refractive index change at the air/glass interface [19,23,24].

Some research to reduce reflection at the glass/TCO interface showed promising results [20,25]. The internal interface between glass and ZnO is less demanding both regarding reliability and angular dependence, therefore a simple single layer quarter-wave ARC [21] can be used. This type of ARC consists of a single layer with a refractive index of $n_{ARC} \approx \sqrt{n_1 n_2}$ where n_1 and n_2 are the refractive indices at the design wavelength in glass and ZnO respectively. The layer thickness should be selected to be $d_{ARC} = \lambda/(4n_{ARC})$ where λ is the design wavelength. The most critical requirement is the refractive index of the ARC material. Possible candidate materials are hydrogenated SiO_x and SiN_x layers deposited in KAI™ PECVD reactors because controlling the amount of oxygen or nitrogen enables modification of the refractive index and the required coating thickness uniformity can be easily achieved. Optimizing the ARC coating for maximum top cell improvement implies a design wavelength of 500 nm thus requiring a material with a refractive index between 1.7 and 1.8 combined with a layer thickness of 60–90 nm.

Reduction of parasitic losses in the TCO layers can be achieved by reducing doping [26], however large area applications increase the requirements on ZnO front contacts by adding an upper limit for the sheet resistance to avoid excessive ohmic losses in modules [27]. Earlier experiments toward reduced parasitic losses were based on a bilayer approach [11,28]. Further improvements need to address a too high TCO resistivity by additional means. Several approaches have been shown in literature: light soaking [29], ultraviolet light exposure [30], annealing [31]; and hydrogen radical treatment [32–35]. Hydrogen radical treatment leads to a significant increase in carrier mobility and a moderate increase in carrier density resulting in better electrical conductivity. This approach gives the possibility to either reduce the sheet resistance (R_{sq}) without affecting the optical properties, or to improve the transmission by lower doping while maintaining the same sheet resistance after treatment.

Light scattering increases light absorption for a given material thickness. Although LPCVD ZnO is considered to be an excellent light scattering material, layers suitable for industrial production require additional compromises. Usually the strong texturization of LPCVD ZnO can lead to crack formation and disturb cell growth [36]. Recent improvements in the microcrystalline silicon deposition process [37] open the opportunity to further optimize ZnO towards better light scattering. Further improvements of light scattering may require the introduction of a textured substrate to decouple light scattering from the TCO surface morphology [38,39], this topic will not be addressed in detail here.

Balancing the top and bottom cell currents is necessary because high efficiency a-Si:H/μc-Si:H tandem photovoltaic devices require high and similar photocurrent generation in the top and the bottom sub-cells because both sub-cells are connected in series. An increase in J_{sc} in a μc-Si:H bottom cell is relatively easy to achieve with the measures mentioned earlier combined with a moderate thickness increase. On the contrary, generating a comparably high photocurrent in the a-Si:H top cell is more challenging. The most difficult limitation is related to light induced degradation (LID): increasing the i-layer thickness to improve J_{sc} will lead to an increase of LID and eventually to a net loss of J_{sc} [40]. To overcome these difficulties both ARCs were optimized for top cell current improvement and we used an intermediate reflector layer (IRL) to controllably reflect light toward the top cell [41,42]. Optimization of the IRL provided high initial top cell current densities, above 14 mA/cm^2 with rather thin *i*-layers below 250 nm. As a result, LID was below 10% for our thin-film record devices [16].

2. Material and methods

The experimental details related to layer deposition and characterization are described elsewhere [7]. Studies of ZnO layers were performed with varying flows of the diethyl zinc (DEZ), diborane (B_2H_6), and water (H_2O) process gases; additionally the hotplate temperature was varied in experiments to identify the optimal layer deposition conditions. A typical LPCVD ZnO layer of 1.7 μm thickness was deposited at 2.55 nm/s deposition rate by using a nominal hotplate temperature of 184 °C, a H_2O/DEZ flow ratio of 1.22, a B_2H_6/DEZ flow ratio of $2.1 \cdot 10^{-3}$ and 0.5 mbar pressure. We report the absolute doping ratio although in the process we use 2% B_2H_6 diluted in hydrogen. Optical transmission, reflection and haze were measured by a PerkinElmer LAMBDA 950 UV/Vis/NIR Spectrophotometer equipped with a 15 cm diameter integrating sphere to collect diffuse light. Haze was determined from the ratio of diffuse transmitted light to total transmitted light at the wavelength of 600 nm. Hydrogen radical treatment based on thermal hydrogen dissociation [43] was performed in a Gen5 chamber developed at TEL Solar in Tsukuba (JP) using following parameters: 200 °C substrate temperature, 10 mbar pressure, 1570 °C catalyzer wire temperature, 2500 sccm H_2 flow, and 900 s treatment time. The density of hydrogen radicals was measured by vacuum ultraviolet absorption spectroscopy (VUVAS) using a NU-Systems Radical monitor and according to a method described elsewhere [44]. Alternatively, hydrogen radical treatment based on plasma-enhanced hydrogen dissociation was performed in a KAI™ reactor using following parameters: 4000 sccm H_2 flow, 0.8 mbar pressure, 0.09 W/cm^2 Radio Frequency (RF) excitation, 200 °C substrate temperature, and 500 s treatment time.

Experiments related to the glass/ZnO iARC were performed in a KAI™ system with 28 mm inter-electrode separation, refractive index was optimized by varying the CO_2/SiH_4 and NH_3/SiH_4 gas flow ratios for the SiO_x:H and SiN_x:H layers, respectively. Both materials were prepared in a low power density, low pressure deposition regime using only Argon as the dilution gas and without adding dopant gases. Typical layers were deposited using an Ar dilution of $Ar/SiH_4 = 20$ at 1.4 mbar pressure using 0.045 W/cm^2 RF excitation and 200 °C substrate temperature.

Experiments related to the IRL were performed in a KAI™ system with 16 mm inter-electrode separation; refractive index and conductivity were optimized by varying the CO_2 and PH_3 gas flows. We report the absolute doping ratio although in the process we use 0.5% PH_3 diluted in hydrogen. Typical IRL layers were deposited using a hydrogen dilution $H_2/SiH_4 \approx 190$, a SiH_4 flow of 87 sccm, 4.7 mbar pressure and 0.24 W/cm^2 RF excitation at 200 °C substrate temperature.

If not otherwise specified, reference MICROMORPH™ cells on ZnO:B substrates were fabricated having 200 nm *i*-layer thickness for the a-Si:H top cell, 105 nm IRL thickness and 1500 nm *i*-layer thickness for the μc-Si:H bottom cell; after cell deposition and laser patterning the devices were laminated. Current–Voltage characterization at AM1.5 conditions was performed using a Wacom two lamp WXS Solar Simulator. External quantum efficiency measurements (EQE) where done using a PV Measurements QEX-10 system. More information on device characterization can be found elsewhere [7]. Light soaking studies were done in a Solaronix Sunirad Class A light soak bench (LSB) at 1000 W/cm^2 and 50 °C device temperature.