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Improved conversion efficiencies of thin-film silicon tandem (MICROMORPH™) photovoltaic modules

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ABSTRACT

Increased electrical power generated from a thin-film silicon (TF-Si) photovoltaic device can lead to a reduced cost of electricity production that will support the mass adoption of this technology as a renewable energy source. Extracting the highest conversion efficiency from 'champion' large area TF-Si modules has been the focus of development at TEL Solar AG, Trübbach. The layer deposition process adjustments and further module technology improvements that led to a significant increase in the absolute stabilized module conversion efficiency of large area (1.43 m^2) tandem MICROMORPH™ modules centered first on obtaining high quality amorphous TF-Si deposited materials for the top cell. This was integrated with microcrystalline TF-Si material for the bottom cell that was deposited under conditions close to the transition point between the amorphous and microcrystalline growth regimes. In an optimized solar cell design the TF-Si materials were then combined with effective light management technologies and an improved module layout. The end result of a world record large area (1.43 m^2) stabilized module conversion efficiency of 12.34% was certified by the European Solar Test Installation (ESTI). The main technology contributions in the device design for this breakthrough result that generated more than 13.2% stabilized efficiency from each equivalent 1 cm^2 of the active area of the full module are described.

1. Introduction

Thin-film silicon (TF-Si) photovoltaic module technology will only realize its potential to be a commercially viable renewable energy source if the cost of electricity production from the module can compete with both existing conventional energy solutions and other renewable energy solutions being developed. The cost of electricity can be reduced by increasing the amount of electricity generated over the useable lifetime of the module, i.e. the energy yield of the module. TF-Si can increase its competitiveness by improving the module reliability so that the end-of-life point (with a consistent definition of this criterion in terms of a threshold percentage reduction relative to the initial performance) is reached as late as possible and second by increasing the electrical power generated by the module. This second quantity is measured by the stabilized module power conversion efficiency (PCE). The MICROMORPH™ technology that was pursued by TEL Solar AG (previously Oerlikon Solar AG) had made significant steps to increase the PCE as part of the continuous drive across the entire photovoltaic community towards higher efficiencies over the last 20 years. Recent progress in efficiencies across all size scales of device size has been reported by Green et al. [1]. Noteworthy benchmarks for the PCE for TF-Si technology include a MICROMORPH™ cell (of area 1.05 cm^2) at 11.5% developed by TEL Solar-Lab SA [2] and tandem cells (a-Si:H/μc-Si:H) at 12.63% and 12.69% developed respectively by EPFL, Neuchâtel [3] and AIST, Tsukuba [4]. For large area modules (aperture area approximately 1.4 m^2) results include at 10.9% module developed by LG Electronics [5] based on a triple junction a-Si/a-SiGe/μc-Si device and recently a large area module (1.43 m^2) published by LG Electronics [6] at

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11.2% (measured at LG) based on the same triple junction a-Si/a-SiGe/μc-Si device.

The present work describes the recent progress made by TEL Solar AG, Trübbach in extending the performance of the MICROMORPH™ technology to significantly higher efficiencies for large area modules. The tandem cell design (a-Si:H/μc-Si:H) behind this technology, originally presented by Meier et al. [7], gives a good compromise between efficient absorption over a wide section of the AM1.5 G solar spectrum and manageable complexity/cost of manufacturing (for equipment, materials and processes). Further development of the plasma enhanced chemical vapor deposition (PECVD) equipment (known as KAI™) by TEL Solar AG [8], enabled new high-pressure deposition processes operating at up to 20 mbar that have resulted in improved material quality for both the top cell (amorphous silicon) and the bottom cell (microcrystalline silicon) absorber layers. These superior layers met production requirements for deposition over a large substrate area (1.1 m × 1.3 m).

The tandem device cell design used in the optimization work described in this paper was a *p–i–n*/*p–i–n* structure. In this simplified description, the device was arranged in the superstrate configuration with commercially available extra-clear 3.2 mm thick float glass and a broadband volume scattering and encapsulating layer at the rear of the layer stack. The top and bottom cell *p–i–n* junctions comprised of PECVD intrinsic amorphous (a-Si:H *i*-layer) and intrinsic microcrystalline (μc-Si:H *i*-layer) absorber layers, respectively. Sandwiching the PECVD silicon layers were the front and back transparent conductive oxide (TCO) layers. The TCO material was boron-doped zinc oxide (ZnO:B) produced with a low pressure chemical vapor deposition (LPCVD) process.

The individual external quantum efficiencies (EQE) for the top a-Si:H and bottom μc-Si:H *p–i–n* junctions and the total EQE of a typical MICROMORPH™ tandem device illustrating the efficient absorption over the AM1.5 G solar spectrum are shown in Fig. 1.

To investigate how far the performance of the MICROMORPH™ technology could be extended to higher efficiencies a construct with the improvements needed to reach at least 12% stabilized module conversion efficiency was defined (in this paper this construct is referred to as a 'bridge' construct). The reference performance (starting point) on a 1.43 m^2 area tandem device was a champion module PCE of 10.7% that was state-of-the-art at TEL Solar AG at the end of September 2013 [9]. From the development potential that existed in the different areas in the tandem cell and module design the necessary improvements to reach 12% efficiency could be partitioned into the module open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}) and *FF* gains required.

Efficient light management in the cell design was a pre-requisite to reach high current densities. The role of anti-reflection coatings (ARC) and transmission-optimized TCO front and back contacts that benefitted higher J_{SC} in the record module are described in this paper. A further contribution to the light management came from scattering of incident light into the cell provided by the high surface roughness of the TCO front contact. It was only possible for such a TCO front contact morphology to be used without compromising the electrical performance of the device (particularly in the bottom cell *p–i–n* junction) in combination with a high quality μc-Si:H *i*-layer material. An optimized design for crystallinity grading in this layer further enhanced the performance achieved from the bottom cell. The development of a high-quality and low-defect a-Si:H *i*-layer was essential to support high J_{SC}, with acceptably low light-induced degradation, and contributed to the overall V_{OC} in the tandem device. A consideration of the ohmic losses in the series interconnection in the large area module provided a mechanism for significantly reducing the module series resistance and increasing the *FF*. This paper describes the record module performance result obtained after these improvements were implemented, and some of the details behind the key steps.

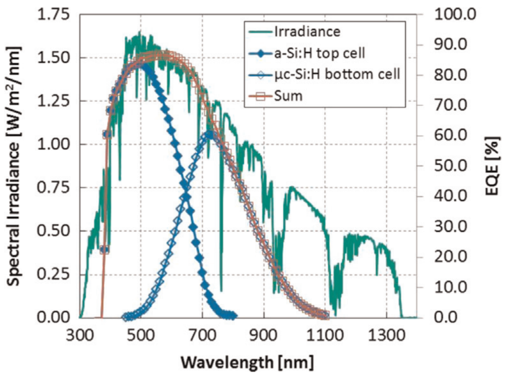

Fig. 1. Example of EQE curves for a MICROMORPH™ tandem device (200 nm thick a-Si:H *i*-layer and 1500 nm thick μc-Si:H *i*-layer) overlaid with the AM1.5 G solar spectrum. EQE was evaluated under reverse voltage bias for each junction cell.

2. Materials and methods

All development and devices that have supported the performance results described in this letter have been produced within the pilot line site at TEL Solar AG, Trübbach. This facility is equipped with a number of production-similar systems for the many different front-end and back-end processing steps described by Roschek et al. [10]. All front-end processes were performed in a cleanroom environment (ISO Class 7), including: substrate cleaning; front and back TCO deposition (LPCVD process); TF-Si PECVD deposition for the top and bottom cell (performed in KAI™ equipment); and interconnect pattern laser scribing. The back-end processes then completed the device with contacting, edge deletion, and lamination. The hardware technologies were largely similar to those used in TEL Solar's ThinFab™ Generation 2 product [11], but in the Trübbach pilot line, the processes and equipment were not optimized for the high throughput requirements of mass production; in particular the substrate was removed from vacuum and exposed to the cleanroom ambient between the deposition steps for the top and bottom cell *p–i–n* junctions.

One of the notable improvements in the Trübbach pilot line hardware was in the design of the PECVD reactors. The conventional PlasmaBox™ design described in the literature [12] was adapted to a use narrow gap reactor technology that benefits the PECVD process by allowing higher process pressures to be supported in the plasma discharge. For the amorphous TF-Si reactor a 16 mm inter-electrode separation allows for process pressures as high as 5 mbar, whilst for the microcrystalline TF-Si reactor a 7 mm inter-electrode separation (equating to a plasma gap above the substrate of 3.8 mm) enables pressures up to 20 mbar. These high-pressure processes were important to obtain the high-quality absorber materials in the tandem device. A description of the narrow gap reactor and its processes can be found in the literature [13].

Thin-film silicon tandem modules with both amorphous and microcrystalline absorbing layers were fabricated in the pilot line using very-high frequency (VHF) excitation at 40.68 MHz in capacitively coupled PECVD KAI™ systems. The thicknesses of the amorphous and microcrystalline absorber layers were in the ranges of 200–250 nm (a-Si:H) and 1.6–2.2 μm (μc-Si:H), respectively. The ratios of the flow rates of H_2 to SiH_4 used in the amorphous and microcrystalline absorber layers were in the ranges of 3-10 (a-Si:H) and 18-32 (μc-Si:H), respectively. An *n*-doped silicon oxide-based (*n*-μc-SiOx:H) material was applied as an intermediate reflective layer (IRL) between the top and bottom cells with a