ACCELERATED PUBLICATION

Record 12.34% stabilized conversion efficiency in a large area thin-film silicon tandem (MICROMORPH™) module

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ABSTRACT

Mass-adoption of thin-film silicon (TF-Si) photovoltaic modules as a renewable energy source can be viable if the cost of electricity production from the module is competitive with conventional energy solutions. Increased module performance (electrical power generated) is an approach to reduce this cost. Progress towards higher conversion efficiencies for ‘champion’ large area modules paves the way for mass-production module performance to follow. At TEL Solar AG, Trübbach, Switzerland, significant progress in the absolute stabilized module conversion efficiency has been achieved through optimized solar cell design that integrates high-quality amorphous and microcrystalline TF-Si-deposited materials with efficient light management and transparent conductive oxide layers in a tandem MICROMORPH™ module. This letter reports a world record large area (1.43 m²) stabilized module conversion efficiency of 12.34% certified by the European Solar Test Installation; an increase of more than 1.4% absolute compared with the previous record for a TF-Si triple junction large area module. This breakthrough result generates more than 13.2% stabilized efficiency from each equivalent 1 cm² of the active area of the full module. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS
photovoltaic; thin-film; silicon; tandem; conversion efficiency; amorphous; microcrystalline

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Received 3 February 2015; Revised 23 March 2015; Accepted 26 May 2015

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, that is, 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 an 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 has been 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 (cell, submodule and large area module) has been reported by M. A. Green et al. [1]. Noteworthy benchmarks for the PCE for TF-Si technology for small area
12.34% stabilized efficiency in a large area module

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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 T. Roschek et al. [10]. All front-end processes were performed in a clean room environment (ISO Class 7), including the following: substrate cleaning; front and back TCO deposition (LPCVD process); TF-Si PECVD deposition for the top and bottom cells (KAI™); 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 a vacuum and exposed to the clean room ambient between the deposition steps for the top and bottom cell p–i–n junctions.

One of the notable advancements present in the Trübbach pilot line hardware was in the design of the PECVD reactors. The conventional PlasmaBox™ design described in the literature [12] has been adapted to use a 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 H₂ to SiH₄ 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. Following the developments made by EPFL, Neuchâtel [14,15], an n-doped silicon oxide-based (n-μc-SiOₓ:H) material was applied as an intermediate reflective layer between the top and bottom cells with a thickness typically in the range of 85-120 nm and a refractive index between approximately 1.9 and 2.0 measured at a wavelength of 600 nm.

The ZnO:B material for the TCO front and back contact layers was prepared using a LPCVD process operating at a...
pressure of approximately 0.5 mbar and nominal hot-plate temperatures between 180 and 190 °C. The ratios of flow rates of the precursor gases of water to diethylzinc (DEZ) were approximately 2.1 and 1.2 for the front and back contacts, respectively. Diborane dopant gas (B₂H₆, 2.0 vol.% diluted in H₂) flow rates were in the ratio to the DEZ flow rates in the range of 2.6 × 10⁻². Resulting TCO layers used in the tandem devices were approximately 1.9-2.5 μm thick.

A broad-band volume scattering and encapsulating layer composed of ethylene-vinyl acetate (EVA) was laid up on the TCO back contact and then the superstrate (with layer stack deposition) was hot-pressed (up to a maximum temperature of 150 °C) under vacuum together with a 2 mm thick glass back-substrate to form the complete laminated module.

Characterization methods for the silicon-based layers and the ZnO:B layers have been described in detail by T. Roschek et al. [10]. Measurements at standard test conditions (25 °C, AM1.5G spectrum, 1000 W/m²) of device JV parameters was made with a Pasan SunSim IIIb solar simulator for large area modules described by M. Apolloni et al. [16]. Light-induced degradation studies for selected large area modules were performed using Hönle SOL-2000 H6 light-soak benches and following the procedures and definitions according to the standard IEC 61646 [17] in order to generate results that could be compared with other published large area module performance [5].

3. RESULTS AND DISCUSSION

3.1. Bridge calculation

The bridge calculation between a starting point of a module PCE of 10.69% and the end goal of at least 12.0% was populated with steps comprising process and technology improvements that had the potential to ‘bridge’ that gap. The starting point tandem module (of area 1.43 m²) was the state-of-the-art at TEL Solar AG at the end of September 2013 [9]. The initial power (P_{ini}) of this module was approximately 167 W and with a stabilized power (P_{stab}) of approximately 152.8 W after 350 h light-soaking. The set of modules had an average stabilized module PCE of at least 12.0% when using a c_{td} assumed equal to 9.0%. The appropriateness of this assumption was separately confirmed from light-soaking data for a set of more than 35 large area (1.43 m²) tandem modules that were produced during the course of the optimization work described in this paper. The modules had been light-soaked according to the procedure and definition given in the IEC 61646 standard [17]; the modules were typically determined as stabilized after not more than 200 h light-soaking. The set of modules had an average stabilized power (P_{stab}) of approximately 167 W and the range in c_{td} was 8.0% to 9.5%.

3.2. Record module performance

The record module was measured in its initial state at TEL Solar AG, Trübbach with a Pasan SunSim IIIb solar simulator, then degraded in a light-soaking bench with irradiance conditions (approximately 1000 W/m²) and module temperature held in accordance with the IEC 61646 standard [17] and finally measured in its stabilized state at the European Solar Test Installation (ESTI). The JV curves and parameters for the initial state measured internally at TEL Solar are shown in Figure 1. A spectral response measurement and mismatch factor correction have been applied as described by M. Apolloni et al. [16].

The performance measurements for the record module in the initial state compare well with the output from the bridge calculation in Table I. The comparison reveals the slightly higher measured P_{meas} of 0.5 W was driven by a slight J_{SC} gain of 0.06 mA/cm² that more than compensated for the small V_{OC} deficit of 3 mV/cell.

Table 1. Bridge calculation for JV parameters to achieve a stabilized module PCE of at least 12.0%. Starting point refers to measured module performance data.

<table>
<thead>
<tr>
<th>JV Parameter</th>
<th>Starting point</th>
<th>End point</th>
<th>Increase (absolute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{OC}/cell [V]</td>
<td>1.412</td>
<td>1.447</td>
<td>0.035</td>
</tr>
<tr>
<td>J_{SC} [mA/cm²]</td>
<td>12.47</td>
<td>13.69</td>
<td>1.22</td>
</tr>
<tr>
<td>FF [%]</td>
<td>71.8</td>
<td>74.0</td>
<td>2.2</td>
</tr>
<tr>
<td>P_{meas} [W]</td>
<td>167.7</td>
<td>193.8</td>
<td>26.1</td>
</tr>
<tr>
<td>PCE_{stab} [%]</td>
<td>10.69</td>
<td>12.36</td>
<td>1.67</td>
</tr>
</tbody>
</table>

PCE, power conversion efficiency; FF, fill-factor.
The optimization that led to a stabilized module PCE of more than 12.0% required more than 300 large area modules to be used in experiments over a 6-month period of time. The development in module performance, for stabilized modules measured and certified at ESTI, is shown in Figure 2. This development spans the time for modules produced in the pilot line from working week (ww) 50 in 2013 to ww26 in 2014.

The degradation coefficient of the record module under light soaking was measured internally at TEL Solar AG with a Pasan SunSim IIIb solar simulator. After 34 h light-soaking, the measured $c_d$ was 6.5%, at 77 h, it was 7.6%, and at the end point defined by the IEC 61646 standard (at 120h), the $c_d$ was 8.1%.

The new world-record performance reported in this letter for a large area (1.43 m$^2$) stabilized module conversion efficiency was measured and certified by ESTI to be 12.34%. The certified performance measurement (corrected to STC 25 °C, AM1.5G spectrum and 1000 W/m$^2$) made at ESTI for this record MICROMORPH™ module is shown in Figure 3. The measurement $J$/$V$ curve and parameters included corrections for module series resistance of 27 Ω and for spectral response according to the measurement procedure performed at ESTI (a spectral mismatch factor of magnitude 0.9884 was applied for the limiting top $p-i-n$ junction determined by ESTI for this module).

The large area module (1.43 m$^2$) layout used for the record module composed of a series interconnection of 196 segments (cells). The module design included an edge deletion width [19] of 11 mm on all sides, a nominal interconnect dead zone width of 200 μm and an active area, determined by ESTI for each segment of 6822 mm$^2$. The stabilized average conversion efficiency calculated for each 1 cm$^2$ of active area on the entire device (with a total active area calculated as 13 371.1 cm$^2$) was reported by ESTI to be 13.2%. This compares favourably with the currently standing world-best performances for a tandem junction TF-Si a-Si/μc-Si cells (approximately 1 cm$^2$ aperture area) of 12.63% and 12.69% developed, respectively, by EPFL, Neuchâtel [3] and AIST, Tsukuba [4].

It should be noted that in the case of performance measurements on small area cells, the use of an aperture mask can lead to small losses of current, or $V_{OC}$ and FF, depending on the precise geometry of the mask and the cell, whereas for the large area module reported here, performance may be also reduced because of small current or $V_{OC}$ losses at the laser scribe interconnections at each of the 196 segments. Variations in the degree of crystallinity in the μc-Si:H i-layer over the whole 1.43 m$^2$ area of the module that have been discussed by J. E. Hötzel et al. [20] contributed to a distribution of conversion efficiency over the 13 371.1 cm$^2$ total active area such that there will have been some 1 cm$^2$ areas of the device with efficiencies greater than the average 13.2% value. Further differences between the published small area cell efficiencies and the large area module performance can perhaps be attributed to the additional light-soaking time used to stabilize the
cells (1000 h at 100 mW/cm²) compared with the requirements of the IEC 61646 standard that was applied to the module. The experience generated from other large area modules used in these experiments, that were degraded for longer times, together with the measured degradation kinetics for the record module, suggested that an additional reduction in absolute efficiency of between 0.25% to 0.35% could be expected if the module would have been light-soaked to 1000 h. Unfortunately because of the closure of TEL Solar AG that was announced at the beginning of 2014, the facilities for extending experiments and measurements for the record module were no longer available after August 2014. Nevertheless, a large area module with an active area of more than 1.3 m² and with an average active area conversion efficiency of 13.2% indicated a very good full-area homogeneity control for all process steps in the module production.

The significant increase in $J_{SC}$ (initial) of more than 1.2 mA/cm² from the starting point module performance was driven by efficient light management in the cell design. Anti-reflection coatings and transmission-optimized TCO front and back contacts generated an approximate $J_{SC}$ increase of nearly 0.8 mA/cm². This was in addition to the increased current already coming from the strongly surface roughness TCO front contact layer. It was only possible to use such a TCO front contact morphology without compromising the electrical performance of the device (particularly in the bottom cell $p-i-n$ junction) in combination with the growth of high-quality $μ$-Si:H $i$-layer material. An optimized design for crystallinity grading in this same layer and an adjustment of the deposition temperature of the top cell $p-i-n$ junction were responsible for enhancing the initial $V_{OC}$ performance in the tandem device by approximately 35 mV/cell. The development of a high-quality and low-defect a-$Si:H$ $i$-layer was essential to support the high $J_{SC}$ and $V_{OC}$, together with obtaining low light-induced degradation. Modelling of the ohmic losses in the series interconnection in the large area module led to a module design change with an increased number of segments and greatly reduced module series resistance that drove the increase in $FF$ demonstrated in the record module. These contributing features to the record module will be discussed in more detail in a later publication [21,22].

4. CONCLUSIONS

A large area (1.1 x 1.3 m) TF-Si photovoltaic module with a tandem junction cell (a-$Si:H$/μc-$Si:H$) was developed to demonstrate the capabilities of the TEL Solar’s MICROMORPH™ technology. Effort was focused on the deposition of high-quality $a$-$Si:H$ and $μc$-$Si:H$ $i$-layers that have promoted good electrical performance, generating open-circuit voltages in the initial state as high as 1.45 V/cell and allowed the scaling of thicknesses of both $i$-layers to support high short-circuit current densities. Light has been efficiently managed in the cell to exploit the maximum potential from thicker $i$-layers with the use of anti-reflection coatings, high-transmission TCO layers that strongly scattered the incident light and optimized doped layers (including an intermediate reflective layer) to generate initial-state current densities above 13.70 mA/cm². The combination of these features resulted in a large area module demonstrating 12.34% stabilized PCE as certified by the ESTI. This result is expected to be presented in the next update of the Solar Cell Efficiency Tables published in the Journal Progress in Photovoltaics: Research and Applications.

ACKNOWLEDGEMENTS

It is a genuine pleasure to thank the many technicians in the TEL Solar AG, Trübbach pilot line who gave considerable time and dedication to help to produce the several hundred modules that were used in this effort to demonstrate more than 12% stabilized module conversion efficiency over the last 9 months.

The authors would like to thank Royal DSM NV for their supply of KhepriCoat® anti-reflection coating that was included in the record module and their effort to apply this material to so many float glass substrates in such a short period of time.

The authors are very grateful to the wider team of engineers from the Tokyo Electron’s Technology Centre, Tsukuba for the supply of more than 700 anti-reflection coated substrates over a 6-month period that were of great use in the initial stages of this development effort.

It is also a pleasure to acknowledge the considerable support from the many colleagues in Product Development in TEL Solar AG, Trübbach, without which, so many of the technical advances described in this letter would not have been possible.

The authors express their appreciation for helpful discussions and exchanges of information with the CSEM (Swiss Centre for Electronics and Microtechnology), IMT (Institute of Microengineering) at the EPFL and TEL Solar-Lab SA, Neuchâtel.

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17. IEC 61646 ed. 2.0 (Section 10.19 Light-soaking). Thin-film terrestrial photovoltaic (PV) modules—design qualification and type approval, 2008.


22. Further information on the research and development conducted at TEL Solar AG towards improving the performance of thin-film silicon photovoltaic modules will be made available at http://thinfilmsiliconpv.ch.