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

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A R T I C L E   I N F O

Article history:
Received 15 April 2015
Received in revised form 18 August 2015
Accepted 24 August 2015

Keywords:
Micromorph
Amorphous silicon
Microcrystalline silicon
Conversion efficiency
Photovoltaic

A B S T R A C T

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 m²) 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 m²) 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 cm² of the active area of the full module are described.

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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 cm²) at 11.5% developed by TEL Solar-Lab SA [2] and tandem cells (a-Si:H/a-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 m²) results include at 10.9% module developed by LG Electronics [5] based on a triple junction a-Si/a-SiGe/m-Si device and recently a large area module (1.43 m²) published by LG Electronics [6] at
technology could be extended to 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 KAITM) 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 m² 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 (VOC), short-circuit current density (JSC) 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 Jsc 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 Jsc with acceptably low light-induced degradation, and contributed to the overall Voc 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.

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 KAITM equipment); and interconnect pattern laser scribing. The back-end processes then completed the device with contacting, edge deletion, and laminating. 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 KAITM 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. 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
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^-4. Resulting TCO layers used in the tandem devices were typically varied in thickness from 1.9 μm to 2.5 μm.

A broadband volume scattering and encapsulating layer comprised 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 Roschek et al. [10]. Measurements at standard test conditions (25 °C, AM1.5 G spectrum, 1000 W/m²) of device JV parameters were made with a Pasan SunSim IIIb solar simulator for large area modules described by Apolloni et al. [14,38]. Light induced degradation studies for selected large area modules were performed using Hönle SOL-2000 H6 light-soak benches (LSB) and following the procedures and definitions according to the standard IEC 61646 [15].

The definition for the degree of crystallinity in the μc-Si:H i-layer used in this paper is the Raman crystallinity factor (ϕc) as defined by Droz et al. [16]. This parameter is closely related to the crystallinity volume fraction as described by Houben et al. [17]. The degree of crystallinity in large area samples was measured by Raman spectroscopy using a Bruker Raman HTS x-y mapping spectrometer. An indication of the quality of the a-Si:H i-layer was determined from the microstructure factor (R) derived from Fourier-transform infrared (FTIR) absorption spectroscopy as defined by Bhattachary et al. [18]. The high quality a-Si:H i-layer material used in the current work typically had an R factor less than 5.0% as discussed in Section 4.

3. Performance prediction

A ‘bridge’ construct gave an estimate of how to increase the module performance from a starting point of an existing champion module PCE of 10.69% to reach the end goal of at least 12.0%. It was populated with steps comprising process and technology improvements that had the potential to ‘bridge’ this gap in the module PCE. The starting point tandem champion 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 (Pini) of this single module was approximately 167.7 W (VOC 1412 mV/cell, JSC 12.47 mA/cm² and FF 71.8%) and with a stabilized power (Pstab) of approximately 152.8 W after 350 hours light-soaking (a relative degradation of 8.8%). The population of the construct with cell or module design features that were targeted to improve current, voltage, fill-factor or combinations thereof, was accomplished through: an internal assessment of the know-how and learning that had been acquired to reach the starting point module performance; by application of some of the advanced add-on technologies already in development at Tokyo Electron Ltd. and TEL Solar [19]; and a review of the current literature and discussions with experts in TF-Si photovoltaics.

The output from this construct formed both a budget and a guide for a series of experiments to validate each potential improvement. A simplified description of the performance prediction is shown in Fig. 2, indicating the targeted improvements in each JV parameter to

![Fig. 2](image-url)
reach the 12% efficiency performance. The construct was intended to show how one might overall significantly increase the module performance by successfully combining the potential gains from several contributing features. Some of these features were very narrow in their approach, e.g. the module layout changes to add more segments with the aim to reduce the impact of ohmic losses in the TCO layers (discussed in more detail in Section 4.2.4). Other features were more complex in implementation, e.g. grading of the μc-Si:H i-layer material to increase $V_{OC}$ in the device whilst mitigating the consequent reduction in $J_{SC}$ by implementation of other features (discussed in Section 4.2.2). The elements in the bridge construct that are shown in Fig. 2 were a mixture of predictions based on: quantifiable theory and experiment, e.g. application of an external ARC was expected to increase the transmission at the air–glass interface by approximately 3% and increase module $J_{SC}$ by the same relative gain (from 12.47 to 12.85 mA/cm² shown in Fig. 2(b)); and on reasonable estimates of gains that might be achieved in other targeted parameters, e.g. a $V_{OC}$ gain of approximately 15 mV/cell through μc-Si:H i-layer crystallinity grading shown in Fig. 2(a). In this last case the prediction was based on previous experimental results achieved at TEL Solar and an understanding of the current literature and discussions with TF-Si photovoltaics experts.

To permit a direct comparison and evaluation for the module performance as quickly as possible the construct exclusively considered the initial performance $JV$ parameters. The stabilized performance was then scaled from the degradation coefficient ($c_{d}$), the measure of the relative change in the module power from the initial to the stabilized states.

The predicted improvement was that a module performance with an initial power of approximately 194 W could be obtained, that scaled to a stabilized module PCE of more than 12.3% when using a $c_{d}$ 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 [15]; the modules were typically determined as stabilized after not more than 200 h light-soaking. This set of modules had an average stabilized power ($P_{stabil}$) of approximately 167 W and the range in $c_{d}$ was 8.0 to 9.5%.

The partitioning of the different contributions in the tandem cell design gave the targeted improvements needed to reach the 12% efficiency performance as: an increase in the module open-circuit voltage ($V_{OC}$) of approximately 35 mV/cell; a gain in the short-circuit current density ($J_{SC}$) of approximately 1.22 mA/cm²; and approximately a 2.2% higher fill-factor ($FF$).

4. Results and discussion

4.1. 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 [15], 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 Fig. 3. A spectral response measurement and mismatch factor (MMF) correction have been applied as described by Apolloni et al. [14,38]. The bottom $p-i-n$ junction was judged to be the current limiting junction in the tandem module as determined from an additional LED backlight measurement system also described in the literature [14,38].

The performance measurements for the record module in the initial state compare well with the output from the prediction shown in Fig. 2. The comparison reveals the slightly higher measured $P_{max}$ of 0.5 W was driven by a slight $J_{SC}$ gain of 0.06 mA/cm² which more than compensated for the small $V_{OC}$ deficit of 3 mV/cell.

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 six month period of time. The development in module performance, for stabilized modules measured and certified at ESTI, is shown in Fig. 4. This development spans the time for modules produced in the pilot line from working week (ww) 50 in 2013 to ww26 in 2014.

The new world-record performance reported in this paper for a large area (1.43 m²) stabilized module conversion efficiency was measured and certified by ESTI to be 12.34% and has been reported in the literature by Cashmore et al. [20]. The certified performance measurement (corrected to STC 25 °C, AM1.5 G spectrum, 1000 W/m²) made at ESTI for this record MICROMORPH™ module is shown in Fig. 5. 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 hours light soaking the measured cd was 6.5%, at 77 hours it was 7.6% and at the end-point defined by the IEC 61646 standard (at 120 hours) the $c_{d}$ was 8.1%. The measurement $IV$ 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 m²) layout used for the record module comprised of a series interconnection of 196 segments (cells). The module design included an edge deletion width [21] 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 mm². The stabilized average conversion efficiency calculated for each 1 cm² of active area on the entire device (with a total active area calculated as 13371.1 cm²) was reported by ESTI to be 13.2%. This compares favorably with the currently standing world-bests performances for a tandem junction TF-Si/a-Si cells (approximately 1 cm² 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 $I_{oc}$ 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 due to small current or $V_{oc}$ losses at the laser scribe interconnections at each of the 196 segments. Further differences between the published small area cell efficiencies and the currently reported large area module performance may be attributed to the additional light-soaking time used to stabilize the cells (1000 hours at 100 mW/cm²) compared to 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 efficiency of between 0.25 to 0.35% could be expected if the module would have been light-soaked to 1000 hours. Unfortunately due to the closure of TEL Solar AG that was announced at 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 an excellent full-area homogeneity control for all process steps in the module production.

### 4.2. Contributing features to the record module

The record module cell design that delivered more than 13% stabilized efficiency from each 1 cm² of active area is shown schematically in Fig. 6.

#### 4.2.1. Top cell amorphous p–i–n junction

The top cell p–i–n junction was responsible for generating two-thirds of the overall stabilized performance in the tandem device and the a-Si:H i-layer was optimized to obtain high-quality and low-defect material. Several series of single-layer depositions on crystalline silicon wafer fragments were made to measure the microstructure factor as an indicator of a-Si:H i-layer material quality, for a variety of different PECVD process conditions within a KAI™ system equipped with a reactor with a 16 nm inter-electrode separation. From the overall trend shown in Fig. 7, lower R factor and improved material quality was obtained at lower deposition rates down to a DR of approximately 1.7 Å/s. The direct comparison of the a-Si:H i-layer materials used in the starting point champion module at 10.7% PCE and the record module at 12.34% showed a significant reduction in R factor down from 4.8% to 3.0% accompanied by the reduction in deposition rate from approximately 2.7 to approximately 1.7 Å/s.

The changes in R factor and DR were correlated with a shift in the PECVD process regime for the record module that included the use of a bi-layer absorber structure shown in Table 1. A high-pressure, high hydrogen dilution regime was used as the first of two layers (approximately 40 nm thick) to promote the initial growth of an a-Si:H i-layer with a low defect density material and benefit both higher $V_{oc}$ and $FF$ in the initial and stabilized states.
The second part of the a-Si:H i-layer was approximately 190 nm thick, deposited at 0.7 mbar process pressure, and was responsible for generating high current densities: $J_{SC}$ (initial) of up to 17.90 mA/cm$^2$ was achieved in an a-Si:H single junction large area module with a total a-Si:H i-layer thickness of 230 nm employing the bi-layer materials shown in Table 1. The improvement in material quality and the bi-layer design contributed towards a record a-Si:H single junction large area (1.43 m$^2$) stabilized module PCE of 9.1% developed at TEL Solar AG, Trübbach and described by Salabas et al. [22,38].

The improvement in material quality also allowed a gain in the top cell p–i–n junction current by increasing the thickness of the a-Si:H i-layer. For a single junction a-Si:H large area module with a 200 nm thick a-Si:H i-layer generating a $J_{SC}$ (initial) of approximately 16.5 mA/cm$^2$, an increase in the i-layer thickness of 30 nm resulted in a gain in $J_{SC}$ of more than 0.35 mA/cm$^2$. A total a-Si:H i-layer thickness of 230 nm supported good initial $V_{OC}$ of as high as 918 mV and had a typical degradation coefficient of approximately 16% after 175 hours light-soaking for the single junction large area module.

Adjustment of the deposition temperature for the entire top cell p–i–n junction contributed to the performance of the tandem module through an improvement in the $V_{OC}$ generated in the amorphous p–i–n junction. The typical trend exhibited for the $V_{OC}$ (initial) measured in a set of tandem submodule devices for a series of deposition temperatures (nominal hot-plate temperature) is shown in Fig. 8(a). Deposition rates and single layer properties were measured at the different deposition temperatures and the PECVD process parameters were adjusted accordingly so that layer thicknesses and other layer properties (for example, the magnitude of the refractive index of the n–μc-SiO$_x$:H-layer) were corrected for the deposition temperature. In reducing the deposition temperature from the standard conditions of 200 °C to 180 °C, the $V_{OC}$ increased by approximately 20 mV/ cell. In Fig. 8(b) the corresponding $J_{SC}$ (initial) data for the same submodule series shows that (for the particular bottom-limited cell design studied) the limiting current of the tandem device was also increasing at lower deposition temperatures possibly due to the increased band-gap in the top cell p–i–n junction. The increased light transmitted to the bottom cell p–i–n junction generated approximately 0.30 mA/cm$^2$ higher current at 180 °C compared to 200 °C, albeit at a comparatively low initial $J_{SC}$ of approximately 11.70 mA/cm$^2$.

The benefit of the decrease in top cell deposition temperature to 180 °C, when integrated in a tandem cell design generating a considerably higher $J_{SC}$ (initial) of 13.20 mA/cm$^2$, was an average increase (for a set of submodules) in $V_{OC}$ (initial) of approximately 24 mA/cm$^2$ as shown in Fig. 9(a) that compares favorably with the prediction of 20 mA/cm$^2$cell shown in Fig. 2(a). The overall average increase in the submodule performance ($P_{in}$), shown in Fig. 9(b) was measured to be 9 mA (approximately equating to an increase of 3 W in a large area module). This increase correlated well to the increase in voltage, as in this cell design the current-matching between top and bottom cell p–i–n junctions was close to the matched condition and only a slight increase in current density (approximately 0.05 mA/cm$^2$) was observed at the lower top cell deposition temperature,

### Table 1

<table>
<thead>
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<th>Layer type</th>
<th>H$_2$SiH$_4$ dilution ratio</th>
<th>RF-power density [W/m$^2$]</th>
<th>Process pressure [mbar]</th>
<th>Deposition rate [Å/s]</th>
<th>$R$ factor [%]</th>
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<td>10.7% PCE module</td>
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<td>223</td>
<td>1.5</td>
<td>2.7</td>
<td>4.8</td>
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<tr>
<td>Record module L1</td>
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<td>208</td>
<td>2.0</td>
<td>2.0</td>
<td>4.0</td>
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<tr>
<td>Record module L2</td>
<td>3.4</td>
<td>101</td>
<td>0.7</td>
<td>1.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>

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The benefit of the decrease in top cell deposition temperature to 180 °C, when integrated in a tandem cell design generating a considerably higher $J_{SC}$ (initial) of 13.20 mA/cm$^2$, was an average increase (for a set of submodules) in $V_{OC}$ (initial) of approximately 24 mA/cm$^2$ as shown in Fig. 9(a) that compares favorably with the prediction of 20 mA/cm$^2$cell shown in Fig. 2(a). The overall average increase in the submodule performance ($P_{in}$), shown in Fig. 9(b) was measured to be 9 mA (approximately equating to an increase of 3 W in a large area module). This increase correlated well to the increase in voltage, as in this cell design the current-matching between top and bottom cell p–i–n junctions was close to the matched condition and only a slight increase in current density (approximately 0.05 mA/cm$^2$) was observed at the lower top cell deposition temperature,
from the bottom cell requires: minimization of shunt paths and effective light scattering; the adjustment of the crystallinity fraction during the growth of the \( \mu c\)-Si:H \( i \)-layer; and the adaptation of processes to enhance the uniformity of the crystallinity across the full deposition area. These points are discussed in greater detail from the bottom cell requires: minimization of shunt paths and effective light scattering; the adjustment of the crystallinity fraction during the growth of the \( \mu c\)-Si:H \( i \)-layer; and the adaptation of processes to enhance the uniformity of the crystallinity across the full deposition area. These points are discussed in greater detail than can be described in this paper by Hötzel et al. [26,38]

Adjustment of the crystallinity fraction in the \( \mu c\)-Si:H \( i \)-layer was investigated as a mechanism to increase \( V_{oc} \) (initial) with a targeted prediction of a 15 mV/cell gain. It has been widely discussed in the literature [27,28,29] how the optimum performance from the \( \mu c\)-Si:H \( i \)-layer can be obtained at a transition point between amorphous and microcrystalline growth regimes. The starting point module cell design that provided a stabilized PCE (for a single module) of 10.7% [9] is shown schematically in Fig. 10 (a). The deposition rate \( (DR) \), extinction coefficient \( (k) \) measured in the single layer at a wavelength of 600 nm, and the approximate Raman crystallinity factor \( (\phi_i) \) for the growth regime are listed alongside the sub-layer approximate thicknesses. It should be noted that with normal deposition conditions, without adjustment of deposition process parameters, the crystallinity volume fraction increases with layer thickness as has been observed by van den Donker [29]. As a consequence of the reduction in passivation of the microcrystalline material by the underlying amorphous material phase the density of defects in the material that can give rise to shunts can be increased. The extinction coefficients stated in this work are accurate for thin single layers (on glass) deposited with the same process parameters as the full device material. The Raman crystallinity factors \( (\phi_i) \) given in this work were measured on the specific \( \mu c\)-Si:H \( i \)-layer as deposited on the full underlying device structure and are appropriate to describe the averaged degree of crystallinity in the volume of material sampled by the 532 nm probe laser of the Raman spectrometer used. The actual crystallinity volume fraction through a 1000 nm thick \( \mu c\)-Si:H \( i \)-layer deposited as part of a full device (and with constant process parameters) can vary considerably throughout the layer and may significantly differ from the measured Raman crystallinity factor.

The basic structure employed in this work consists of: a thin \( i \)-layer adjacent to the bottom cell \( p \)-layer with moderately high crystallinity that supported the subsequent layer crystallinity uniformity; followed by the bulk \( \mu c\)-Si:H \( i \)-layer that was close to the amorphous transition regime; and finally a thin \( i \)-layer that was fully amorphous (at least to the extent allowed by the conditions in the 20 mbar narrow gap PECVD reactor that strongly favors microcrystalline-growth regimes). Further discussion of this structure and the functionality of the sub-layers can be found in the literature [26,38].

The potential to increase \( V_{oc} \) (initial) by adjusting, in a step-wise manner, a specific profile of crystallinity grading of the \( i \)-layer was explored. A parameter study was conducted based on splitting the bulk \( i \)-layer into two approximately equal thickness sub-layers and varying the Raman crystallinity factor \( (\phi_i) \) between the two parts, principally by using different set-points for the SiH\(_4\) precursor gas flow rate in each sub-layer. The relevant conditions of the variations evaluated are shown in Table 2. Ellipsometer measurements (not detailed in this paper for reasons of brevity) of single \( \mu c\)-Si:H \( i \)-layers on glass were used to guide the extent of the SiH\(_4\) flow rate setting in the sub-layers in the tandem devices.

A set of tandem submodule devices were fabricated with the step-wise crystallinity grading conditions of the \( \mu c\)-Si:H \( i \)-layer shown in Table 2. The top cell \( p-i-n \) junction was kept constant throughout with a 200 nm thick \( a\)-Si:H \( i \)-layer and 105 nm thick IRL. Measurements of \( V_{oc} \) and \( J_{sc} \) in the initial state are shown in Fig. 11. A strong progression in the \( V_{oc} \)/cell and decline in \( J_{sc} \) with an increase in the total SiH\(_4\) flow rate in the \( \mu c\)-Si:H \( i \)-layer agreed with the previously observed trends in the extinction coefficient for the single layer ellipsometer measurements, confirming that the crystallinity of the layer decreased rapidly with increasing total

---

**Table 2**

<table>
<thead>
<tr>
<th>Experiment Condition</th>
<th>( i )-layer structure</th>
<th>( i )-layer thickness [nm]</th>
<th>Adjustment in SiH(_4) flow rate [sccm]</th>
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</thead>
<tbody>
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<td>1</td>
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<td>1100</td>
</tr>
<tr>
<td>2</td>
<td>Reduced deposition rate</td>
<td>bulk</td>
<td>1100</td>
</tr>
<tr>
<td>3</td>
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<td>( i_{2b} )</td>
<td>550</td>
</tr>
<tr>
<td>4</td>
<td>RDR ( i_{2a} )</td>
<td>( i_{2b} )</td>
<td>550</td>
</tr>
<tr>
<td>5</td>
<td>RDR ( i_{2a} )</td>
<td>( i_{2b} )</td>
<td>550</td>
</tr>
<tr>
<td>6</td>
<td>RDR ( i_{2a} )</td>
<td>( i_{2b} )</td>
<td>550</td>
</tr>
</tbody>
</table>

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**Fig. 10.** Schematics of the bottom cell \( \mu c\)-Si:H \( i \)-layer structure and approximate thicknesses for (a) the starting point cell design at a PCE of 10.7% and for (b) the record module cell design with a PCE of 12.34% (note: not drawn to scale).

**Fig. 11.** Plot of tandem submodule device (a) \( V_{oc} \)/cell and (b) \( J_{sc} \) (both in the initial state and averaged over a set of submodules) for the bulk \( i \)-layer crystallinity grading variations shown in Table 2.
SiH$_4$ flow rates. The slight increase in the average initial $V_{oc}$ (approximately 3 mV) and the significant decrease in the $J_{sc}$ (approximately 0.30 mA/cm$^2$) that was observed in the shift from the standard deposition rate of 7.7 Å/s to the reduced deposition rate of 4.0 Å/s also suggested a reduction in the crystallinity of the $i_2$-layer occurred in the regime change to lower deposition rates. However, this did not correlate with the approximately constant magnitude of the extinction coefficient ($k=0.23$) measured on the ellipsometer for the two single µc-Si:H $i_2$-layers. As these single layers were only approximately 220 nm thick it again highlighted the significant difference between the crystallinity inferred from thin single layer measurements and the actual crystallinity volume fraction present in a bulk layer that was intended to be used in the final device. Additional and more accurate measurements in real device layers would be needed to make a proper assessment of the actual crystallinity grading. The extent of how far the SiH$_4$ flow rate adjustment could be reasonably extended was observed in the final experiment (6) condition. At an increase in, the $i_{2a}$- and $i_{2b}$-layers of +10 sccm and +15 sccm SiH$_4$ flow rate, respectively, the average $V_{oc}/cell$ was no longer increasing and exhibited increased scatter over the set of submodules. More significantly the average $J_{sc}$ fell sharply indicating the onset of instability in the deposition regime and the uncontrolled appearance of fully amorphous material in localized regions over the substrate area as described by Hötzel et al. [26,38].

In order to expedite the progress towards achieving the record module a compromise between $V_{oc}$ gain and managing the $J_{sc}$ decrease led to the decision to use the known process parameters defined from experiment (5) in the record module, rather than intermediate SiH$_4$ flow rates that might be suggested from a full ‘design of experiment’ analysis of these results. Experiment (5) conditions with $i_{2a}$- and $i_{2b}$-layers of +5 sccm and +10 sccm higher SiH$_4$ flow rates, respectively, gave a $V_{oc}/cell$ gain of approximately 16 mA above the reference, which compares well with the improvement expected from the bridge construct of a 15 mV gain shown in Fig. 2(a).

The thickness of the µc-Si:H $i$-layer was increased to attempt to reach the $J_{sc}$ gain required from the performance prediction described in Section 2 (after first recovering the approximate 0.8 mA/cm$^2$ current lost from the selected crystallinity grading). Previously established scaling relationships between the µc-Si:H $i$-layer thickness and $J_{sc}$ (initial) from a series of bottom $p$–$i$–$n$ junction-limited tandem large area modules showed that approximately 0.35 mA/cm$^2$ higher current density was generated for each additional 200 nm thickness of bulk µc-Si:H $i$-layer up to a total $i$-layer thickness of approximately 2000 nm. The same series showed only a slight weakening of the built-in voltage in the tandem module with a decrease in the $V_{oc}/cell$ of less than 1 mV per 200 nm of additional bulk µc-Si:H $i$-layer. To meet the performance prediction from the bridge construct in Fig. 2(b), the final thickness for the entire µc-Si:H $i$-layer stack was chosen to be 2000 nm; with the exact structure of the sub-layers as shown in Fig. 10(b).

### 4.2.3. Light management

The management of the incident light and the distribution of current generation in the tandem device was an important optimization step in reaching the high conversion efficiencies reported in this paper. The complex interaction between current generation in the $i$-layers in the top and bottom $p$–$i$–$n$ junctions was managed with the adjustment of the $i$-layers’ thicknesses, and supported by the layers’ material quality and their stability under light-soaking. Some of the light management functions in the record module cell design included: anti-reflection coatings on the external (here termed as eARC) and internal (here termed as iARC) surfaces of the front glass superstrate; transmission optimized TCO front and back contacts; and an optimized $n$-µc-SiO$_2$:H-layer at the end of the bottom cell $p$–$i$–$n$ junction (not discussed in this paper due to reasons of brevity). In addition an intermediate reflective layer (IRL) was inserted between the top and bottom cells with the benefit of increasing the light absorption path through the amorphous layer so a given µc-Si:H $i$-layer thickness can be used to generate current comparable to that of a thicker layer. However, since the IRL has a broad reflective spectrum the benefit for the top cell comes at the expense of reducing the light transmitted to the µc-Si:H $i$-layer and therefore lowering the bottom cell generated current. A proper optimization of the IRL thickness and refractive index to reach high conversion efficiencies is not discussed in this paper but more details are described by Losio et al. [25,38].

A measure of the effectiveness of the light management features developed for the record 12.34% PCE module and an indication of the further potential is shown in Table 3. The maximum integrated $J_{sc}$ that can be obtained from the AM1.5 G spectrum, without any optical losses, was calculated up to the nominal cut-off wavelength (800 nm) for the a-Si:H single junction device. This was compared with the measured initial $J_{sc}$ of 17.90 mA cm$^{-2}$ for the record a-Si:H single junction large area (1.43 m$^2$) module with stabilized PCE of 9.1% [22,38]. The utilization ratio of 65.6% (measured $J_{sc}$ divided by the maximum available $J_{sc}$) for this module showed that approximately one-third of the available current was lost. This loss was most likely a result of the following factors: parasitic absorption mainly in the ZnO:B front and back contact layers as well as a smaller amount lost in the $n$- and $p$-doped layers; reflection of unused light out of cell; and charge carrier collection and recombination losses. The comparison for an µc-Si:H/µc-Si:H tandem junction device was made using a nominal cut-off wavelength of 1100 nm and a simplified assumption that the total $J_{sc}$ (the sum of the current densities in the top and bottom $p$–$i$–$n$ junctions) in the actual tandem module was equal to twice the measured $J_{sc}$ (initial) of the limiting junction. The estimated utilization ratio for the record tandem large area module with stabilized PCE of 12.34% was approximately 63%. A similar calculation for the starting point champion module with PCE of 10.69% gave an estimated ratio of approximately 57% and showed the significant improvement in the light management that was achieved in the current work.

It may be noted that the real utilization ratio for the tandem modules would have been higher than the value quoted in Table 3 since the record module was measured to be bottom-limited in the initial state; therefore the $J_{sc}$ of the top $p$–$i$–$n$ junction was higher than the 13.75 mA/cm$^2$ value measured from the JV curve for the entire device. EQE measurements were not available for the record module cell design but a reasonable estimate was made for the top $p$–$i$–$n$ junction current density of 15.5 mA/cm$^2$ that led to a utilization ratio of above 67%. A more sophisticated calculation for the short-circuit current of silicon solar cells developed by Tiedje et al. [30] (termed the Tiedje–Yablonovitch limit) includes radiative recombination and other fundamental losses (Auger recombination and free carrier absorption). Zeman et al. [31] reported the Tiedje–Yablonovitch $J_{sc}$ limit for a µc-Si:H $i$-layer thickness of 2800 nm as 35.32 mA/cm$^2$. Applying this limit for the available $J_{sc}$
from the AM1.5 G spectrum further improves the light management utilization ratio for the record module to more than 82%.

An external anti-reflection coating (eARC) based on slit-coating of a porous SiOx-based layer was applied to large area 1.43 m² float glass substrates in Tokyo Electron Ltd.’s Tsukuba facility before these were shipped to the TEL Solar’s Trübbach pilot line for insertion into the standard module production sequence described by Roschek et al. [10]. The optical coating was targeted to be a λ/4-type single layer with a refractive index of approximately 1.3 designed for a wavelength of 500 nm. Measurement of the transmission spectra of the two coatings showed a relative increase in total transmission (integrated over a wavelength range of 400–1100 nm) over the bare glass reference of approximately 2.5% [25].

The impact of the anti-reflection coating on large area tandem modules is displayed in Fig. 12. The top cell p–i–n junction comprised a 220 nm thick a-Si:H i-layer, together with a 105 nm thick IRL and a bottom cell p–i–n junction with total thickness of the μc-Si:H i-layer of 1600 nm and a structure based on the configuration shown in Fig. 10(a). The increase in J_sc of 0.38 mA/cm² equated to a 3.0% relative gain in close agreement with the performance prediction shown in Fig. 2(b). The overall improvement in module performance (P_m) of 4.1 W shown in Fig. 10(b) was a 2.4% relative increase. The differences in total transmission, J_sc gain and P_m gain were explained by a decrease in FF as a result of a shift in current-matching between the top and bottom p–i–n junctions towards slightly closer matching, from the original bottom-limit configuration.

An alternative anti-reflection coating based on commercially available material (KhepriCoat® developed by Royal DSM NV) was also evaluated. The technology of this coating has been described in the literature [32]. For the coating that was supplied on float glass substrates to TEL Solar AG, Trübbach, the peak optical transmission was tuned to target a peak wavelength of 500 nm or 550 nm. Measurement of the transmission spectra of the two coatings showed a relative increase in total transmission (integrated over a wavelength range of 400–1100 nm) over the bare glass reference of approximately 2.9 and 2.8%, respectively [25,38].

The comparison of the performance of two anti-reflection coating materials on large area tandem modules is seen in Fig. 13. The top cell p–i–n junction comprised a 230 nm thick a-Si:H i-layer, together with a 98 nm thick IRL and a bottom cell p–i–n junction with total thickness of the μc-Si:H i-layer of 2000 nm and a structure based on the configuration shown in Fig. 10(b). The optical performance of the two coatings when integrated into the tandem modules was similar with only a very slight increase in J_sc of 0.01 mA/cm² for the DSM coating. There was an overall improvement in module performance (P_m) of 2.6 W shown in Fig. 13(c) (approximately a 1.4% relative increase) that was driven entirely by an improvement in FF shown in Fig. 13(b) of just over 1% absolute. Cell limitation measurements confirmed that there was no significant difference in the strongly bottom-limited matching state of the two modules. Examination of their JV curves showed a significant improvement in the parallel resistance (R_p) of the module with the DSM coating. The inset in Fig. 13(d) shows a reduction in the slope of the JV curve at the J_sc-point by approximately 35% equating to the same magnitude increase in the value of R_p. A visual inspection of both modules showed a cleaner surface for the DSM coating and measurements with infrared lock-in thermography (LIT) of the modules showed significantly fewer shunts with this coating. The DSM coating appeared to collect less of the small amounts of surface contaminants that were unavoidably introduced during some of the manual process steps in the Trübbach pilot line facility. A DSM coating was the solution adopted for the 12.34% efficiency modules.
be a $\lambda/4$-type single layer with a refractive index of approximately 1.75 measured at a wavelength of 500 nm and with an approximate thickness of 72 nm. Measurement of the transmission spectra of this coating showed a relative increase in total transmission (integrated over a wavelength range of 400–1100 nm) over the bare glass reference of approximately 1.6% [25,38].

The impact of the internal anti-reflection coating on tandem submodule devices is shown in Fig. 14. The top cell $p-i-n$ junction comprised a 210 nm thick a-Si:H $i$-layer, together with a 105 nm thick IRL and a bottom cell $p-i-n$ junction with total thickness of the $\mu$c-Si:H $i$-layer of 1800 nm and a structure based on the configuration shown in Fig. 10(b). The average increase in $J_{SC}$ shown in Fig. 14 of 0.21 mA/cm² equated to a relative gain of 1.6% indicating that the iARC was performing slightly better than the prediction of a 1.45% relative gain given from the bridge construct shown in Fig. 2(b).

A significant amount of the light incident on the photovoltaic module was typically lost in parasitic absorption within the ZnO:B TCO front and back contact electrodes as reported by Losio et al. [25,38]. Reduction of the boron dopant concentration within the TCO layer can significantly improve the optical transmission but at the expense of reducing the electrical conductivity of the layer and increasing ohmic losses in the module. An approach to improve the conductivity in low-doped material, by treating the TCO with hydrogen plasma treatment of the TCO front and back contacts is shown in Fig. 15 for a set of submodules fabricated with multi-layer TCO FC and BC (Reference) and hydrogen plasma treated, low-doped TCO FC and BC (TCO FC + H-plasma).

in $J_{SC}$ (initial) of approximately 0.30 mA/cm² was obtained with the H-plasma treated TCO that matched to the prediction shown in Fig. 2(b). This gain was slightly reduced to approximately 0.26 mA/cm² after more than 700 h of light-soaking of the submodules.

A further contribution from light management to the current generated in the $\mu$c-Si:H $i$-layer of the bottom cell was the high-haze of the front TCO layer. With a rough surface morphology provided by the LPCVD growth regime of the ZnO:B material, the typical haze measured in the range of 45 to 50%. Slightly lower high haze layers (in the range of 40 to 45%) were also included in the 10.7% starting point module design. The relative increase of the initial module $J_{SC}$ measured in the bottom cell for a 45% haze front TCO layer compared to a reference 28% haze layer was reported by Losio et al. [25,38] to be up to 5%. This equates to a contribution of approximately 0.68 mA/cm² at the record module $J_{SC}$ (initial) level of 13.75 mA/cm². At the same time only a small (less than 1% relative increase) benefit on the current density measured in the top cell $p-i-n$ junction was observed.

4.2.4. Layout adjustment

A first-order consideration of the loss factors in a monolithic series interconnected TF-Si module has been reported by several authors [35,36] where a description was given of relative power loss terms for the interconnection dead area and ohmic (resistive) losses in the TCO front and back contact layers. Application of this calculation methodology to the large area module layout used at TEL Solar AG, Trübbach showed that the potential existed to gain approximately 3.5 W by increasing the number of segments from 142 to 196, as reported by Cervetto et al. [37,38]. The power gain could be equated to an effective reduction in the module series resistance from the decrease in ohmic losses and then scaled to an increase in fill-factor (that also included a power loss correction for the increase in total dead area losses). This mechanism was included in the performance prediction described in Section 3 to estimate an increase in FF (initial) for a large area module with 196 segments of 1.6% (absolute) compared to the 142 segment layout.

The comparison of the performance of the different layouts on large area tandem modules with the same cell design is shown in Fig. 16. The top cell $p-i-n$ junction comprised a 230 nm thick a-Si:H $i$-layer, together with a 98 nm thick IRL and a bottom cell $p-i-n$ junction with total thickness of the $\mu$c-Si:H $i$-layer of 2000 nm and a structure based on the configuration shown in Fig. 10(b). A very
small decrease in $J_{SC}$ (initial) of approximately 0.01 mA/cm² was measured as shown in Fig. 16(a) that was within the measurement noise of the Pasan SunSim IIb solar simulator. Significant increases in FF (initial) and in $P_{max}$ of approximately 1.8% (absolute) and 3.0 W, respectively, were measured and were in reasonable agreement with the original prediction shown in Fig. 2(c). The result confirmed the decision to use a 196 segment layout for the record module.

5. Conclusions

A large area (1.1 m x 1.3 m) thin-film silicon photovoltaic module with a tandem junction cell (a-Si:H/µc-Si:H) was developed to demonstrate the capabilities of the TEL Solar MICROMORPH™ technology. Effort was focused to develop 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 above 1.44 V/cell, and allowed scaling of thicknesses of both i-layers to support high short-circuit current densities. Light was efficiently managed in the cell to exploit the maximum potential from the thicker i-layers with the use of anti-reflection coatings, transmission-optimized TCO layers, 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 power conversion efficiency as certified by the European Solar Test Installation. This result has been reported in Version 46 of the Solar Cell Efficiency Tables [1] published by the Journal Progress in Photovoltaics: Research and Applications. It is also perhaps interesting to speculate on the further potential that remains for the MICROMORPH™ technology based on the progress that was made in this work. In selected high-performing modules ($P_{m}$ above 187 W), open-circuit voltages in the initial state above 1.455 V/cell were achieved. In other high-performing modules with slightly increased thicknesses of a-Si:H and µc-Si:H i-layers an initial-state current density of as high as 14.15 mA/cm² was measured. With assumptions that a similar FF can be achieved as for the record module reported in this work and a similar degradation coefficient to the record module (both of which are not unreasonable considering the high-quality a-Si:H and µc-Si:H i-layers deposited here), then stabilized power conversion efficiencies of above 12.9% could be within reach.

Acknowledgments

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.

The authors would like to thank Royal DSM NV for their supply of their KhepriCoat™ anti-reflection coating 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 seven hundred anti-reflection coated substrates over a six 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 Micro-engineering) at EPFL and TEL Solar-Lab SA, Neuchâtel.

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