Microcrystalline bottom cells in large area thin film silicon MICROMORPH™ solar modules


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1. Introduction

Amorphous thin film silicon solar cells do not make use of the full potential of the AM1.5 spectrum: with a bandgap of ≈ 1.75 eV their spectral response is limited to the range of ≈ 300–800 nm. [1] The interval of the absorption spectra and the absorption efficiency can be extended by combining the amorphous cell with one or more additional sub-cells of smaller bandgaps which are sensitive in the longer wavelength regions of the AM1.5 spectrum [1]. Microcrystalline silicon (µc-Si:H) with a bandgap of 1.1 eV is sensitive up to ≈ 1100 nm and it is therefore a suitable candidate for extending the spectral response in a double junction or MICROCRYPHTM [2] solar device.

The focus of this paper is put on the development, the optimization and the evolution of the microcrystalline sub-cell at TEL Solar over a period of more than 3 years. The amorphous top cell, the results on the MICROCRYPHTM tandem development and the world record on MICROCRYPHTM large area modules based on the microcrystalline sub-cell are reported elsewhere [3–7]. Recent progress has been made in the development of microcrystalline cells using various PECVD deposition systems and cell configurations. AIST presented in 2014 and 2015 microcrystalline world record solar cells in n-i-p configuration deposited in a multi-chamber system [8,9], the latest cells had an efficiency of 11.8% achieved with a Voc of 548 mV, a Jsc of 29.4 mA/cm² and a FF of 73.1%. In 2013 IMT in Neuchâtel published a microcrystalline record cell with an efficiency of 10.69%.[10] The cell of ≈ 1 cm² generates a Voc of 549 mV and a Jsc of 26.6 mA/cm² with a FF of 73.3% on a 1.8 μm thick device. In the same report the IMT group challenged the limits of Voc and Jsc in microcrystalline devices achieving a very high Voc of 608 mV on a cell with a thickness of ≈ 0.6 μm and a remarkable Jsc of 29.1 mA/cm² on a 3.3 μm thick cell, both cells with 0.25 cm² active area [10]. The latter cells give an outlook on the potential if the device is optimized for single current-voltage (IV) parameters.

High Jsc and high Voc at the same time are required for high efficiencies devices. Jsc can be more easily tuned to higher values compared to Voc by increasing the thickness of the intrinsic absorber layer, on the contrary significant increasing Voc requires to improve the µc-Si:H material quality. Both Voc and Jsc are sensitive to the Raman crystallinity (Rc) profile of the intrinsic µc-Si:H absorber layer. Solar cells of comparable material quality will gain in Voc if the Rc profile of the intrinsic absorber layer is tuned to lower levels.

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values e.g. toward the amorphous region but the $V_{oc}$ gain is achieved at the expense of losing $J_{sc}$ and vice versa. For a constant set of deposition parameters the $R_c$ will change with increasing layer thickness, to counteract this behavior inherent of microcrystalline silicon thin film growth it is common practice to change the deposition parameters during growth. The changing of deposition parameters, usually called grading is often described in literature: to this day it is accepted that best module efficiency is achieved when $R_c$ of the microcrystalline intrinsic layer is between 45% and 60% or nearby the so called “transition phase” with an a-Si:H and μc-Si:H mixed phase material [11–16].

In this paper in contrast to maintaining $R_c$ constant throughout the total thickness of the device a different type of grading will be reported. The fundamental design principle is the supposition that if the material quality and the deposition uniformity of the intrinsic absorber layer are on a reasonable good level a balanced maximum of high current generation and simultaneously high $V_{oc}$ can be achieved by separating the single i-layer into sub-layers dedicated to improve $V_{oc}$ or $J_{sc}$.

The bottom cell quality, in particular, the quality of the bottom cell i-layer is of crucial importance for improving the efficiency of MICRO-MORPH™ devices. The quality of microcrystalline material is extensively discussed in literature and, dependent on the various types of defects, many parameters and methods are proposed for its characterization. Defects may range from the atomic scale, like dangling bonds, which are one of the most important ones [18] and are typically studied by FTPS to larger defect types like cracks [21] affecting the whole bulk and cell thickness. The detrimental impact of defects always result in the reduction of one or more solar cell parameters $V_{oc}$, $J_{sc}$, and $FF$ and it may be detectable already in the initial state or later in the stabilized or light soaked state. In this paper the intrinsic μc-Si:H material quality of MICRO-MORPH™ devices is assessed mainly in a phenomenological way by measuring and comparing the IV parameters of solar devices. A section on microscopic analysis is added to support and complement this approach.

Various methods for improving the microcrystalline material quality can be found in literature. The electronic properties and crystallinity can be improved by reducing the deposition rate [22]. Increasing the deposition pressure enables the deposition of high quality μc-Si:H material without decreasing the deposition rate but can result in powder formation which is detrimental for the quality of the deposited films [20,22]. By reducing the inter-electrode gap distance both powder formation [20] as well as the formation of higher silane radicals, which affects the material quality, can be strongly reduced [23]. High quality material in combination with high deposition rates can be achieved [24] and the gas utilization efficiency is increased helping in the overall economic balance [25]. By proper tuning of the plasma conditions e.g. high pressure depleted plasma (HPD), the defect density can be kept on a reasonable level with significantly increased deposition rate compared to the standard low pressure method [18,22]. Another way to achieve low defect densities is reducing the ion energy below the threshold energy for defect formation by increasing the excitation frequency [17]. A higher frequency leads to a higher electron density and simultaneously to a lower electron temperature [26] which is advantageous for the promotion of the crystal growth [20], additionally the SiH₄ utilization can be increased at higher frequencies [27] which has positive impact on the production cost. Additional parameters and conditions which influence the material quality and the conversion efficiency of a microcrystalline photovoltaic device are the silane concentration [18,20], combined with the total gas flow and the flow regime, the deposition rate and the substrate or reactor temperature [18].

The thin film technology of TEL Solar is originally based on a VHF-PECVD (very high frequency PECVD) parallel plate PlasmaBox™ reactor with an inter-electrode distance of 28 mm, working pressure of 250 Pa, an excitation frequency of 40.68 MHz, and $1.4 \times 1.2$ m² electrode surface to deposit the microcrystalline bottom cell. The complete system is known as KAI™ [19]. With this system and process configuration the limits of efficiency with respect to deposition rate, material quality and the economic aspects have been reached at ~138 Wp stabilized for MICRO-MORPH™ tandem devices. Starting from the KAI™ platform three potential ways for improving material quality, preserving or increasing deposition rate and efficiency would be possible: increasing the process pressure, decreasing the interelectrode gap; and increasing the excitation frequency. The latter would require a much more expensive electrode design to achieve the required uniformities on large areas and was assessed not to be compatible with industrial production and cost. Early reactor development activities therefore have been focused on achieving higher deposition pressures.

In the original KAI™ system working pressures $\leq 250$ Pa have been explored so far and optimized MICRO-MORPH™ tandem devices with a $V_{oc}$ of typically 1330–1340 mV could be realized. Estimating the single contributions from the top and the bottom cell to $V_{oc}$ leads to a contribution from the bottom cell of 430–440 mV cell assuming that a top cell approximately contributes with 900 mV. The difference between the IV results especially $V_{oc}$ obtained with 28 mm gap and the ones obtained for the cells of AIST [8,9] and IMT [10] is more than 100 mV. This huge gap already gives reason to the presumption that with the original version of the KAI™ system and the associated industrial processes it is not possible to close the gap.

TEL Solar therefore has followed the approach to successively increase the process pressure and to gradually reduce the inter-electrode gap avoiding powder formation and keeping the excitation frequency constant at 40.68 MHz.

The inter-electrode gap was reduced from 28 mm first to 16 mm and then to 7 mm for allowing higher process pressures [25]. Parameters like applied power and reactor temperature were also modified in order to obtain the best possible cell for a given geometry.

Table 1 reports the calculation for two extreme process conditions in terms of possible pressure, flows and RF power and summarizes the accessible process windows and plasma parameters of the three reactors with different inter-electrode gaps used for this study.

The residence time and the Yasuda parameter [28] are comparable for all three reactors in the particular extremes. Since all of the depositions in this study were based on SiH₄ and not on higher silanes, the Yasuda parameter is given in the form “Power/Flow”.

One parameter which is changing significantly going from 28 mm to the 7 mm gap reactor is the power density: when reducing the gap from 28 mm to 16 mm the power density changes by approximately a factor 2. A further increase of factor 3–4 is achieved by reducing the gap from 16 mm to 7 mm.

Finally, the silane usage which is a relevant parameter for cost in mass production can be increased from 30% to 95%. The strong increase when replacing KAI 28 with KAI 7 can be qualitatively explained in the frame of a global model as described by Lieberman and Lichtenberg [29]. The increase of the process pressure should lead to a strong decrease of the electron temperature. Nonetheless the reduction of the reactor gap, and consequently the increase of the ratio reactor surface/reactor volume should lead to an increase of the electron temperature. Consequently the electron temperature in case of KAI 7 might be expected to be not very far away from the electron temperature in case of KAI 28. Some internal simulation results beyond the scope of this contribution confirmed this supposition. The increase of the volume density of the applied power will lead to an increase of the
the deposition regime changes from pressure limited and consequently to an increase of the deposition rate. Practically the redevelopment of all layers. The main parameters to tune the working pressure, the silane concentration and consequently to an increase of the density of SiH₄ radicals and the electron density. The increase of the partial SiH₄ pressure in conjunction with the said behavior of electron temperature and electron density leads to an increase of the density of SiH₄ radicals and consequently to an increase of the deposition rate. Practically the deposition regime changes from pressure limited to flow limited.

2. Material and methods

The full device, process flow and the characterization of the MICROMORPH™ tandem devices in this paper are described elsewhere [3,19]. This paper summarizes experiments over a period of more than three years of development therefore the experimental conditions changed during the time. For this reason IV parameters of devices described in the single experiments can be different in range, even if they are from the same reactor and in some cases parameters have been normalized. To explore regimes with a reduced inter-electrode gap, new PECVD reactors needed to be developed and each change in the reactor hardware required the redevelopment of all layers. The main parameters to tune the layer properties like dᵣ, Rᵣ, uniformity of the μc-Si:H i-layer are: working pressure, the silane concentration SC, total gas flow and RF power. Additional tuning parameters for the doped p and n layers are the flows of doping precursors Trimethyl Borane TMB (C₃H₉B) or Phosphine (PH₃).

The microcrystalline solar devices which are described within this work are always designed in order to be integrated as the bottom cell in the MICROMORPH™ tandem device. Three different test devices have been used: large area modules (substrate size: 1.3 × 1.1 m², depending on module layout from 99 to 196 cells connected in series, cell areas are specified in the text), sub-modules (substrate size: 10 × 10 cm², total active area 37.87 cm², 10 cells connected in series) and cells of 1 cm² active area. The process development on large area modules requires and uniform deposition of the layers on the whole surface.

This paper describes experiments with reactors with varying electrode gaps. The reactors will be differentiated by the terms KAI 28, KAI 16 and KAI 7 indicating the use of reactors with inter-electrode gaps of 28 mm, 16 mm and 7 mm respectively. KAI 28 is the original standard reactor described above and in [19]. The KAI 16 reactor, based on the platform of KAI 28 is operated at 40.68 MHz and up to pressures of 750 Pa. The inter-electrode gap distance of 16 mm is the smallest possible gap without the need for major redesigns of the system and it is determined by mechanical limits of the glass loading procedure and by the overall system design.

For working pressures higher than 1000 Pa KAI 7 is used which is a new reactor concept very different from the KAI 28 and the KAI 16. The reactor with an inter-electrode gap of 7 mm is operated at 40.68 MHz with and working pressures between 1000 Pa and 2000 Pa can be applied. For comparing devices from different process regimes or reactors the cell design and the thickness of the sub-layers were identical.

To describe MICROMORPH™ tandem devices an abbreviation system will be used. As an example “220/IRL/1200”: the first figure indicates the thickness in nm of the amorphous intrinsic absorber layer of the top cell, the abbreviation IRL stands for intermediate reflector layer and it is used only if the layer is present. Finally the second figure indicates the thickness in nm of the intrinsic microcrystalline absorber layer of the bottom cell.

For the development of microcrystalline modules, a device needs to be combined with an amorphous top cell. However, to study single microcrystalline devices in conditions as similar as possible to the real tandem configuration but independently of the electrical influence of the top cell and independently of the matching condition of top and bottom cell current a special vehicle named “filtered bottom cell” was developed. In this approach the a-Si:H top cell in the tandem device is replaced by an amorphous n-doped optical filter layer which has similar optical absorption properties and similar structure of a top cell but without adding any contributions to Vₘ and Jₘ. The conductivity of the filter layer is sufficiently high to completely extract the bottom cell current.

The Rc characteristics of the intrinsic μc-Si:H absorber layer has a major impact on the solar cell parameters and the efficiency. Raman crystallinity (Rₘ) in large area samples was measured by Raman spectroscopy using a Bruker Raman HTS x-y mapping spectrometer (532 nm laser) and calculated using the method described in literature [30], the penetration depth of the probing laser is estimated to be around 100 nm for layers with high Rc and as low as 20 nm for completely amorphous layers. To perform the Rc measurement under the same conditions which are present in a tandem device the μc-Si:H i-layers were deposited on the full underlying stack of layers of a real tandem device, including the transparent conductive oxide (TCO). In most cases the Rc measurement was done prior to the n-layer deposition. Especially Rc profiles were measured by preparing a series of samples with increasing intrinsic layer thickness and measuring each sample. In some cases the measurement was made through the final n-layer, actually the n-SiOₓ-layer which is deposited on the μc-Si:H i-layer. In such case a negative offset of ~5–10% on the value of Rc has to be taken into account due to the low crystallinity of n-SiOₓ. The Rc values for modules and sub-modules given here are averaged values. On sub-modules typically three measurements at different locations were taken whereas for large area modules typically a matrix of 13 × 15 evenly spaced measurement points has been used for calculating the average Rc value. In standard deposition conditions for which the reactors are tuned for, this measurement technique is appropriate to calculate the average Rc. With process conditions approaching the transition to amorphous silicon deposition the deposition uniformity suffers and local spots of up to totally amorphous material could appear. These local spots are not

### Table 1
Calculated plasma parameters like residence time, power density, Yasuda parameter and silane usage for the three different reactors (gaps) in extreme conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KAI 28</th>
<th>KAI 16</th>
<th>KAI 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter electrode gap [mm]</td>
<td>28</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>Plasma gap [mm]</td>
<td>25</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Pressure range [Pa]</td>
<td>400</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>SiH₄ flow range [scm]</td>
<td>200</td>
<td>10000</td>
<td>1000</td>
</tr>
<tr>
<td>H₂ flow range [scm]</td>
<td>4000</td>
<td>4000</td>
<td>2000</td>
</tr>
<tr>
<td>SiH₄ usage range [%]</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Reactor temperature best cell [°C]</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Residence time [s]</td>
<td>1.62</td>
<td>0.32</td>
<td>0.17</td>
</tr>
<tr>
<td>Rower density [W/cm²]</td>
<td>0.089</td>
<td>0.044</td>
<td>0.171</td>
</tr>
<tr>
<td>Yasuda parameter [W/ccm(plate)]</td>
<td>20</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

fully taken into account by the measurement matrix due to the comparatively large spacing between measurement points but they are fully reflected in the IV parameters of such a device. Therefore some IV results will suddenly show an unexpected decrease in $J_{sc}$ which is caused by such amorphous regions. For further details of the characterization of layers and devices see [3,19].

When comparing different devices in one experiment it is required that the thickness of the sublayers are the same, which is easy to realize; and that the $R_{c}$ profiles are comparable, which needs elaborate tuning, to generate an equal $J_{sc}$. When these conditions are met, $V_{oc}$ is a sensitive measure of the quality of the microcristalline material. $J_{sc}$ is as well an indicator of material quality but it is more sensitive to small changes in thickness and in the $R_{c}$ profile. When comparing two devices with same absorber thickness where the first device, the reference, has a similar but lower $R_{c}$ profile compared to the second device and $J_{sc}$ of the second device is increased, as expected but without the loss of $V_{oc}$ or $FF$ then this is as well a clear signature of an improved microcristalline material quality (cf. Table 3). The gain in current could be attributed to a lower recombination rate due to a reduction of recombination centers e.g. a reduction of the dangling bond density which is an improvement in material quality.

Microscopic analysis was performed at EMPA Dubendorf, Switzerland using a FEI Strata DB235 dual beam focused ion beam (FIB) and secondary electron microscope (SEM); Scanning Transmission Electron Microscope (STEM) pictures were prepared using a Jel 2200FS TEM/STEM system. Electron microscopy images were post-processed in Imagej; background correction was done using the slope background removal function and the local contrast was enhanced using the contrast limited adaptive histogram equalization (CLAHE) method [31,32].

3. Experiments, results and discussion

TEL Solar evaluated a strategy comprising three steps to realize higher pressures in different reactor configurations:

1. Push to the limits the existing hardware (KAI 28), particularly the tradeoffs between material quality and uniformities deriving from increasing the pressure above 250 Pa for which the reactor is optimized. The deposition pressure was increased to the point of maximum module efficiency.
2. Perform moderate hardware changes in terms of cost, time and compatibility with and on the existing reactor platform (KAI 28) to reduce the inter-electrode distance to 16 mm (KAI 16). The maximum power of MICROMORPH™ devices given by such platform was determined.
3. The third step is the development of a totally new reactor concept. This concept is very flexible and allows in theory the reduction of the gap to the very mechanical minimum. A gap of 7 mm was chosen for the KAI 7 reactor.

3.1. Increasing pressure: KAI 28

The μ-Si:H i-layers of the bottom cell deposited in KAI 28 (250 Pa) with deposition rates between 2.8 and 6.5 Å/s allowed best initial cell efficiency of typically 10.6%. Bugnon [33] reports on significant improvement of the material quality of microcrystalline cells deposited in a similar reactor by increasing the process pressure from 120 Pa to 250 Pa and 350 Pa. The conclusion is that the reduction of sub-band gap absorption coefficient measured by FTPS lead to the improvement of the μ-Si:H material quality which he attributed to the weaker ion bombardment resulting from increased working pressures. In the first approach the deposition pressure in the KAI 28 was increased in four steps from 250 Pa to 620 Pa (330 Pa/400 Pa/550 Pa). The μ-Si:H i-layers were analyzed and optimized for uniform deposition. The deposition uniformity of $R_{c}$ and the layer thickness $d$ on the substrate (1.4 m²) deteriorated with increasing pressure. Severe non uniformities of $R_{c}$ appeared from 400 Pa onward to higher pressures. For pressures above 500 Pa the deposition conditions could not be tuned in order to achieve a uniformity of $R_{c}$ suitable for producing full size modules. Comparing IV the results for the best MICROMORPH™ cells (220/900) from processes at 250 Pa and 330 Pa in Table 2 a significant increase in $V_{oc}$ and a minor increase in $J_{sc}$ and $FF$ can be shown for the higher pressure deposition process. The results point out the potential for a relative efficiency increase in the range of 5–6% by increasing the working pressure. The deposition rates for the μ-Si:H i-layers, 3.6 Å/s for the 330 Pa process compared to 4.2 Å/s for the 250 Pa process are slightly different. Out of experience of variations of $d$, from $\sim$1 to 9 Å/s only a minor efficiency increase can be attributed in reducing the deposition rate of about $\sim$14%, e.g. for a performance increase of $\sim$5% the deposition rate has to be intentionally reduced by 60% (see further results in Section 3.6.1). The large gain in $V_{oc}$ is an indication of an improved material quality. On large area MICROMORPH™ module level (220/900) the best efficiency was achieved at 330 Pa with a relative gain of 1.75% compared to the reference. The drop of the relative gain from 5.9% to 1.75% is caused by the lower uniformity of the deposition at 330 Pa for both layer thickness and $R_{c}$. Applying the process pressure of 400 Pa an efficiency level comparable to the reference at 250 Pa could be realized despite the worse layer uniformity properties at 400 Pa. The huge gap between the relative gain in efficiency on module and cell level illustrates the importance and the potential of an uniform deposition. The KAI 28 hardware was designed and optimized for process pressures of 250 Pa for microcrystalline depositions. The uniformity at higher pressures could have been further improved in a certain range by optimizing the reactor design to the specific pressure regimes but to take the second step of reducing the electrode gap in the existing reactor was considered to be the more promising way.

Table 2

<table>
<thead>
<tr>
<th>Reactor</th>
<th>KAI 28</th>
<th>KAI 16</th>
<th>KAI 28</th>
<th>KAI 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ [Å/s]</td>
<td>4.2</td>
<td>3.6</td>
<td>4.2</td>
<td>3.6</td>
</tr>
<tr>
<td>$V_{oc}$ [V]</td>
<td>1.329</td>
<td>1.375</td>
<td>1.12</td>
<td>1.132</td>
</tr>
<tr>
<td>$J_{sc}$ [mA/cm²]</td>
<td>71.6</td>
<td>72.0</td>
<td>10.6</td>
<td>11.2</td>
</tr>
<tr>
<td>FF [%]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>$Eta$ [%]</td>
<td>9.3</td>
<td>11.2</td>
<td>10.6</td>
<td>11.2</td>
</tr>
</tbody>
</table>

The KAI 7 reactor is optimized. The deposition pressure was increased to the point of maximum module efficiency.

Table 3

<table>
<thead>
<tr>
<th>Reactor</th>
<th>KAI 28</th>
<th>KAI 16</th>
<th>KAI 28</th>
<th>KAI 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Bot$ cell [nm]</td>
<td>900</td>
<td>1200</td>
<td>900</td>
<td>1200</td>
</tr>
<tr>
<td>$Top$ cell [nm]</td>
<td>220</td>
<td>220</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>IRL No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pressure [Pa]</td>
<td>330</td>
<td>700</td>
<td>330</td>
<td>700</td>
</tr>
<tr>
<td>$DR$ bot [Å/s]</td>
<td>4.5</td>
<td>4.8</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td>$Eta$</td>
<td>1.034</td>
<td>1.040</td>
<td>1.092</td>
<td>1.092</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>1.098</td>
<td>1.001</td>
<td>1.003</td>
<td>1.003</td>
</tr>
<tr>
<td>$J_{sc}$</td>
<td>1.038</td>
<td>1.043</td>
<td>1.086</td>
<td>1.086</td>
</tr>
<tr>
<td>FF</td>
<td>0.998</td>
<td>0.996</td>
<td>1.003</td>
<td>1.003</td>
</tr>
</tbody>
</table>

The 7 mm was chosen for the KAI 7 reactor.
3.2. Reducing gap distance and increasing pressure: KAI 16

Intrinsic microcrystalline single layers were developed in different process pressure regimes in KAI 16 with the starting point at 330 Pa for comparison with KAI 28. The process pressure was increased to 500 Pa and finally to 750 Pa. For pressures up to 700 Pa the uniformities of the layer thickness $d$ and $R_c$ are much less impacted by increasing the process pressure compared to KAI 28 which again emphasizes the importance of the reactor design optimized to a certain pressure regime. Like in KAI 28 the efficiency is not increasing linearly with the process pressure. The maximum in efficiency or the best MICROMORPH™ and filtered bottom cell modules in the pressure interval of 350–750 Pa could be realized with process pressure of 700 Pa.

To demonstrate the impact of pressure and gap on the quality of the microcrystalline bottom cell two sets of large area modules (128 cells in series, $A_{cell}=103.9 \, \text{cm}^2$), all with state-of-the-art-champion-process-conditions, have been realized. The first module set comprises an amorphous top cell with a 220 nm thick intrinsic amorphous absorber layer and a bottom cell with an intrinsic microcrystalline absorber layer of 900 nm (220/900). The top cells of both modules are fabricated the same way and in the same reactor (KAI 28). The bottom cells were produced either in a KAI 28 or in a KAI 16 reactor. The cell structure for both bottom cells is comparable in terms of number, thickness and sequence of sub-layers. In the second set, top cells including an IRL were chosen to achieve higher efficiencies. The intrinsic absorber layer of the bottom cells therefore had to be thicker in order to compensate the less incoming light from the top cell. 220/IRL/1200 of the bottom cells therefore had to be thicker in order to compensate the less incoming light from the top cell. 

For both cell structures the "high pressure-small gap" module results show a clear improvement of the efficiency compared to the same cell structure setup with the microcrystalline cell deposited in the "low pressure-large gap" reactor KAI 28. For the "high pressure-low gap" condition the results in Table 3 show a relative gain in efficiency of 5.2% for the 220/IRL/1200 modules and a relative gain of 3.4% for the 220/900 module compared to the "low pressure-large gap" condition. Analyzing the IV parameters in Table 3 in detail, $V_{oc}$ and $F_f$ remain constant and do not change significantly, only a major gain in $J_{sc}$ is noticeable. The $R_c$ profile of the KAI 16 deposition could be shifted slightly to a more crystalline fraction which improves $J_{sc}$. A large gain in $J_{sc}$ simultaneously preserving $V_{oc}$ and $F_f$ on a constant level is the result of an improved material quality. With the step to a higher deposition pressure and at the same time reducing the inter-electrode gap to 16 mm the efficiency of the MICROMORPH™ modules could be increased significantly compared to the results of KAI 28. Nevertheless comparing the IV parameters, especially the typical $V_{oc}$ of ~1375 mV of the best MICROMORPH™ large area modules realized in KAI 16 with the record cells of AIST [8] and IMT [10] reveal that there is still potential for improvement. The pressure of 700 Pa is not high enough to reach 530–550 mV in the microcrystalline bottom cell.

3.3. Further increasing pressure and reducing gap: KAI 7

For achieving and working with process pressures far beyond 700 Pa neither KAI 28 nor KAI 16 could be used. Changing the reactor hardware to the KAI 7 was the next mandatory step for the exploration of process pressures > 700 Pa. The material quality of microcrystalline layers was investigated by producing a series of sub-modules deposited at different process pressures, all with the same layer setup in the filtered bottom cell configuration to avoid the influence of the top cell. To avoid the influence of differing Raman profiles on $J_{sc}$ only sub-modules with single i-layers having a similar profile and $R_c=52–57\%$ were chosen. The modules were selected by measuring $R_c$ at three different positions on the module directly before depositing the back contact.

The module power (Fig. 1) increases with increasing the deposition pressure from 1000 Pa up to 2000 Pa. The improvement is mainly driven by the gain of $F_f$ and $V_{oc}$ which indicates improving material quality with increasing pressure. $J_{sc}$ is almost constant for 1000–2000 Pa which is the result of the very narrow Raman crystallinity interval. At 2500 Pa local non-uniformities of $R_c$ and the appearance of the previously discussed amorphous spots lead to a reduced $J_{sc}$. As a consequence, the performance slightly drops from 2000 Pa to 2500 Pa. Nevertheless $F_f$ and $V_{oc}$ are still on the high level. The appearance of amorphous spots is a sign that the process is approaching the hardware design limits, therefore hardware optimization for a pressure of 2500 Pa could further lead to an increase of IV performance.

Silane flow or silane concentration is another important parameter which has impact on the material quality of the μc-Si:H i-layer, on $R_c$, and on $J_{sc}$ of the resulting solar device. For testing the influence of the deposition pressure for different silane flows with constant hydrogen flow on the device performance, a set of MICROMORPH™ large area modules, all with a single μc-Si:H i-absorber layer (no intentional grading) has been produced with 1800 Pa and 2000 Pa (Fig. 2).

The difference in process pressure of ~10% results in ~7% power difference. For all module results the higher pressure deposition always leads to a better performance. The $I_{sc}$ curves (triangles in the bottom pane of Fig. 2) for 1800 Pa and 2000 Pa are almost identical which indicates that the crystallinity profile for the two modules which are compared is similar. $V_{oc}$ starts from the same level and increases almost linearly with increasing silane...
flow for both working pressure series but with different slopes. For the process pressure series of 2000 Pa the slope of $V_{oc}$ is steeper and the $FF$ is always higher compared to the $\mu$-Si:H I-layer deposited at 1800 Pa which again is an indication for a better material quality. For both working pressures the shape of the single IV parameters as a function of the silane flow is similar: $V_{oc}$ and $FF$ are increasing with increasing silane flow or concentration. $I_{sc}$ is decreasing slightly because of decreasing crystallinity of the absorber layer; as shown in Fig. 3. Finally, the module power is increasing with increasing silane flow. At a silane flow of 240 sccm a sharp drop of $I_{sc}$ occurs and leads to a sharp drop of power. In Fig. 3 the extinction coefficient $k$ and two $R_e$ curves, all averaged over the large area glass substrate, are plotted over the silane flow from 190 sccm to 290 sccm. The two $R_e$ measurements are either including or excluding local amorphous spots which appear due to non-uniformities in the deposition. The linear behavior of $k$, plotted without the amorphous spots corresponds to the linear behavior of $R_e$ excluding local amorphous spots. At a silane flow of 240 sccm the $R_e$ curves start to split. The appearance of local amorphous spots result in a sharp drop of $R_e$ compared to the $R_e$ value where these local spots are excluded for the calculation of the average $R_e$. The sharp drop of $I_{sc}$ in Fig. 2 at 240 sccm is caused by this drop in $R_e$. The qualitatively expected behavior of $I_{sc}$ without the presence of the amorphous spots is indicated by the dashed-dotted line in Fig. 2.

### 3.4. IV results for low, intermediate and high pressure processes in KAI 28, KAI 16, and KAI 7

Table 4 below summarizes a set of experiments realized with sub-modules. The only difference between sub-modules is the bottom cells deposition done either in KAI 28, KAI 16 or KAI 7. The averaged IV parameters are given in the initial and the stabilized state after approximately 1000 h of light soaking. $V_{oc}$ clearly increases when increasing deposition pressure and lowering the electrode gap; additionally a moderate increase of $J_{sc}$ and $FF$ can be obtained too. The improved performance for devices from KAI 7 compared to devices from KAI 16 and KAI 28 is preserved in the stabilized state. Despite the higher deposition rates for the devices deposited in KAI 7, a 10% relative increase in stabilized efficiency is obtained compared to the efficiency of the devices from KAI 28.

The efficiency of MICROMORPH™ modules could be increased $\geq 1\%$ absolute in efficiency, by increasing the working pressure from 250 Pa to 2000 Pa and reducing the electrode gap from 28 mm to 7 mm. The stabilized $V_{oc}$ reached on our large area record module (1.4 m$^2$) [3] is $V_{oc}=1429$ mV which corresponds to $\sim 530$ mV coming from the bottom cell. This is comparable to record results on cells of $\sim 1$ cm$^2$ obtained by AIST [8] and IMT [10].

### 3.5. Material quality analysis: comparison of results at different gaps and pressures

In the previous chapters the material quality of microcrystalline layers has been evaluated qualitatively and indirectly by comparing IV results of solar devices. Alternatively material quality can be qualitatively assessed by microscopic analysis. Cross sections of MICROMORPH™ devices deposited in KAI 28 and KAI 7 with process pressures of 330 Pa and 2000 Pa respectively were exposed by FIB milling and SEM pictures are shown in Fig. 4. Both samples were processed with the same type of glass substrate, TCO front contact (28% Haze) process and the same type of back contact. Both microcrystalline devices were deposited on the same type of top cell with similar bottom cell process conditions.

The SEM cross section of the device deposited in a KAI 28 reveals voids in the crystalline material known in the literature as “cracks” [21,34]. In contrast the $\mu$-Si:H device deposited in a KAI 7 does not exhibit such features. Similar results were consistently observed in several cross sections.

Using a flat TCO with zero Haze prepared according to a method described elsewhere [35] (not shown here), neither the device from KAI 7 nor the device deposited in KAI 28 shows cracks confirming that the morphology of the growing base plays an essential role. Cracks and voids reduce the electrical performance of devices [21] and enable post-oxidation having detrimental effects on $FF$ and $V_{oc}$ [34]. Therefore minimizing the crack density is mandatory for high efficiency $\mu$-Si:H solar cells. As an example of the detrimental effects of cracks, the initial IV parameters of sub-modules prepared from the same substrates used to obtain the cross sections shown in Fig. 4 are shown in Table 5.

The parameters $V_{oc}$ and $FF$ from devices deposited in KAI 7 are...
Table 4
Averaged initial IV parameters and stabilized IV parameters after approximately 1000 h light soaking of MICROMORPH™ sub-modules with μc-Si:H bottom cells deposited in KAI 28 at 330 Pa, KAI 16 at 700 Pa and in KAI 7 at 2000 Pa working pressure. Besides the μc-Si:H bottom cell the devices are prepared with the same type of glass substrate, TCO front and back contact and top cell. The deposition rates for KAI 28 and KAI 16 are similar whereas the deposition rate of KAI 7 is significantly increased. "dr" indicates the deposition rate and is given as range of typical values, "top/bot" indicates the thickness of each cell, "rel. dev." indicates the relative deviation.

<table>
<thead>
<tr>
<th>Pressure [Pa]</th>
<th>KAI</th>
<th>top/bot [mm/mm]</th>
<th>$d_r$ [Å]</th>
<th>Light soaking [h]</th>
<th>$P$ [mW]</th>
<th>$V_{oc}$ [V]</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>FF [%]</th>
<th>Eta [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>28</td>
<td>220/1200</td>
<td>[4.2,4.5]</td>
<td>0</td>
<td>427</td>
<td>13.26</td>
<td>11.69</td>
<td>72.8</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1070</td>
<td>368</td>
<td>13.15</td>
<td>11.37</td>
<td>65.1</td>
<td>9.7</td>
</tr>
<tr>
<td>700</td>
<td>16</td>
<td>220/1200</td>
<td>[4.4,4.9]</td>
<td>0</td>
<td>457</td>
<td>13.64</td>
<td>11.76</td>
<td>75.3</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1070</td>
<td>378</td>
<td>13.41</td>
<td>11.46</td>
<td>64.9</td>
<td>10.0</td>
</tr>
<tr>
<td>2000</td>
<td>7</td>
<td>220/1200</td>
<td>[5.8,7.1]</td>
<td>0</td>
<td>466</td>
<td>13.95</td>
<td>11.93</td>
<td>74</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>989</td>
<td>404</td>
<td>13.80</td>
<td>11.64</td>
<td>66.4</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Table 5
Averaged initial IV parameters of MICROMORPH™ sub-modules fabricated from the samples described in Fig. 4 with μc-Si:H bottom cells deposited in KAI 28 with 330 Pa and in KAI 7 with 2000 Pa working pressure. Apart from the μc-Si:H bottom cell the devices are prepared with the same type of glass substrate, TCO front contact (28% Haze), back contact, and top cell.

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Pressure [Pa]</th>
<th>$V_{oc}$ [V]</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>FF [%]</th>
<th>Eta [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAI 28</td>
<td>330</td>
<td>13.09</td>
<td>11.72</td>
<td>70.2</td>
<td>10.8</td>
</tr>
<tr>
<td>KAI 7</td>
<td>2000</td>
<td>13.91</td>
<td>11.55</td>
<td>73.5</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>rel. dev. [%]</td>
<td>6.3</td>
<td>−0.7</td>
<td>4.8</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Fig. 4. Cross sections prepared by FIB of two MICROMORPH™ devices deposited in (a) KAI 28 at 330 Pa and (b) KAI 7 at 2000 Pa. The flat glass substrate is at the bottom (not visible), the TCO front and back contacts are shown (brighter areas). The front contact for both samples exhibit a Haze of 28% and the top cells for both samples are similar. Disruptions in the crystalline growth are highlighted by the dashed ovals. Images were post-processed to enhance the contrast and highlight defects.

Fig. 5. Schematic preparation of the μc-Si:H lamella for STEM characterization. The μc-Si:H lamella is prepared by FIB milling, micromanipulators are used to extract the lamella and place it on a carbon-coated copper grid.

significantly higher compared to the $V_{oc}$ and FF from devices deposited in KAI 28. This can be directly correlated with the lower density of cracks and therefore with the better material quality of the high pressure deposition in KAI 7.

Cracks shown in Fig. 4 are not one dimensional or columnar: in fact they build a network of defects following the valleys defined by the underlying ZnO pyramids as recently shown by post processing a series of FIB cross-sections [36]. Without resorting to several cross sections and extensive image reconstruction, it is possible to qualitatively study crack networks by preparing a FIB lamella parallel to the substrate surface approximately at half of the μc-Si:H i layer thickness as shown schematically in Fig. 5. In practice two samples are glued together with the glass substrates facing the outside. A diamond coated saw is used to prepare a rough cross section which is then carefully polished. FIB milling can then be used to prepare a lamella for STEM analysis.

Since high performance MICROMORPH™ devices require high Haze [3–5], cracks were studied in a solar cell prepared in a KAI 7 at 2000 Pa on 45% Haze ZnO and compared to an earlier device prepared in a KAI 28 at 330 Pa on a 28% Haze ZnO. Cross sections were prepared and images obtained by STEM in High Angle Annular Dark Field (HAADF) mode are shown in Fig. 6. HAADF provides a signal dependent on material density: high density regions appear light and low density regions appear dark.

A cross section of a device prepared in the KAI 28 shown in Fig. 6a reveal an extensive network of dark lines (e.g. low density) which can be attributed to cracks. A further magnification – Fig. 6c – reveals that the dark lines are often interconnected and additional thinner lines appear. On the contrary, a cross section shown in Fig. 6b of a device prepared in the KAI 7 on a higher Haze ZnO reveals significantly less dark regions. A magnification of an area containing some dark lines – Fig. 6d – shows that the dark regions are narrower and less interconnected compared to KAI 28, even in spite of the higher Haze used in KAI 7. These observations are qualitative; however they support other observations presented in this work suggesting an improved material quality of devices produced in KAI 7 compared to KAI 28. The obtained material is more dense, compact and homogenous matching the literature suggestions for good microcrystalline material quality. A more detailed and quantitative analysis would require analyzing several more images and it is beyond the scope of this work. The method of preparing horizontal cross section allows however to easily observe the width and interconnectivity of cracks at high resolution.

Another effect which is related to the μc-Si:H material quality is
the so-called “Dark Degradation” which is discussed more in depth elsewhere [37]. Dark degradation is the effect of decreasing IV parameters even when modules are kept in controlled dark room conditions where light induced degradation is excluded. Dark degradation is correlated to the degradation of the bottom cell due to effects like post oxidation [34] where $V_{oc}$ and $FF$ are degrading but not exclusively. Some types of dark degradation of the bottom cell can be detected by EQE measurements where the bottom cell shows a decreasing response. Affected modules, depending on the matching state between top and bottom cell could show a decrease in $J_{sc}$. Modules with bottom cells deposited in KAI 28 exhibited dark degradation when using e.g. high TCO Haze values and other process conditions where the correlation with the dark degradation mechanism is not yet fully understood in detail. Changing the bottom cell deposition to KAI 16 the modules did not exhibit measurable dark degradation independently of the deposition regime or module design.

3.6. Bottom cell optimization

The previous sections demonstrated the improvements in material quality achieved by reducing the inter-electrode distance and increasing the process pressure. Good material quality itself is a prerequisite for further efficiency improvement of $\mu c$-Si:H or MICROMORPH™ tandem devices. The key part of a $\mu c$-Si:H device is the intrinsic absorber and the ability of controlling and tuning the absorber layer is essential for high efficiency. Optimizations of the deposition rate, of the Raman crystallinity and of the crystallinity profile in KAI 7 reactors will be presented in the following sections.

3.6.1. Deposition rate

The deposition rate is relevant for device performance and for determining the production costs of a module. In general a lower deposition rate leads to a lower density of defects [18] and thus to higher performance. However the cost of each module increases due to a longer production time, therefore for economical calculations, the balance between stabilized module power (related to material quality) and tact time has to be found.

A series of filtered bottom cell sub-modules with a single $\mu c$-Si: H i-layer was prepared using deposition rates between $d = 3 \text{ Å/s}$ and $8 \text{ Å/s}$ to empirically study the effect of the deposition rate on material quality and on module efficiency. The initial averaged IV results are presented in Fig. 7. All modules were prepared with $R_c$ in the range between 47% and 57% measured before back contact deposition. $FF$ and $V_{oc}$ are increasing with decreasing deposition rate which is the result of improving $\mu c$-Si:H material quality due to the better growth conditions [18].

$J_{sc}$ is increasing with decreasing deposition rate from 8 Å/s down to 5 Å/s but from 5 Å/s down to 3 Å/s $J_{sc}$ inverts the tendency and start to decrease. The decline of $J_{sc}$ for $d_i < 5 \text{ Å/s}$ is due to layer non-uniformities or amorphous regions discussed.

![Fig. 6. Horizontal cross sections of MICROMORPH™ devices imaged by STEM in HAADF mode. Left column (a, c): deposition in KAI 28 at 330 Pa on ZnO with 28% Haze; light gray ribbons originate from the supporting carbon foil. Right column (b, d): deposition in KAI 7 at 2000 Pa on ZnO with 45% Haze. Top row (a, b): scale bar is 500 nm, the dashed squares indicate the region magnified in (c, d). Bottom row (c, d): scale bar is 100 nm. Images were postprocessed to remove the background, enhance contrast and to adapt brightness across the four pictures.](https://example.com/fig6.png)
previously which are becoming more pronounced in these deposition regimes. The resulting module performance seems to saturate for \(d_s \leq 5 \, \text{Å/s}\). A performance increase of approximately 5% could be realized when reducing \(d_s\) by \(\sim 60%\) from 8 Å/s to 5 Å/s. A linear extrapolation to even lower \(d_s\) of 3 Å/s indicates a possible further potential for improvement. However, additional hardware modifications to improve the layer uniformity for the process conditions at very low deposition rates are required to fully exploit this potential. Reducing the deposition rate leads to an improved efficiency up to the point where the reactor design is limiting the uniform distribution of properties of the deposited layers (i.e. local thickness or \(R_c\)).

### 3.6.2. Raman crystallinity

In the following experiment the maximum efficiency was determined as a function of \(R_c\) for sub-modules with single \(\mu c\)-Si:H i-layers (see Section 3.6.1) on filtered bottom cells. Modules with a wide range of the averaged \(R_c \sim 25–65\%\), measured at the end of the cell deposition through the n-SiO\(_x\)-layer were realized by a variation of the silane flow while keeping the H\(_2\)-flow constant (5C from 4.4% to 6.7%). The corresponding initial IV parameters were measured and plotted in Fig. 8. FF and \(V_{oc}\) decrease almost linearly with increasing \(R_c\). \(J_{sc}\) is increasing but the slope deviates from the dashed line which is a linear fit of \(J_{sc}\) for \(R_c > 40\%\). Here (for \(R_c < 40\%\)) the deposition conditions reach the limitations of the hardware and layer uniformity is not satisfactory for depositions on 1.4 m\(^2\). Best module power is achieved using \(SC = 5.8\%\) and 0.26 W/cm\(^2\) reaching a measured crystallinity of \(R_c \sim 45–50\%\) which corresponds to \(R_c \sim 50–55\%\) in the intrinsic bulk similarly to what is reported in literature [1,12]. The sub-modules with the highest power show a \(V_{oc}\) of approximately 530–540 mV which is similar to the recently published results of AIST and IMT [8,10].

An intrinsic microcrystalline absorber layer fabricated with constant deposition parameters will exhibit only a fraction of the \(\mu c\)-Si:H i-layer in the ideal transition region due to the evolution of \(R_c\) as a function of layer thickness as shown in literature [38–40].

### 3.6.3. Grading

To introduce a grading of the i-layer properties, the i-layer is successively subdivided into sub-layers and each sublayer thickness and \(R_c\) is optimized while maintaining the total i-layer thickness constant.

In a first step the single i-layer is divided into two sub-layers \(i_1\) and \(i_2\). The deposition parameters of the \(i_1\) layer are optimized to promote the onset of crystalline growth. When a crystallinity level of \(R_c \sim 45–50\%\) is reached the deposition parameters are changed and optimized to maintain this crystallinity level throughout the rest of the deposition. This is in agreement with literature [11,12].

In a second step which suggests an alternative to literature it will be demonstrated that intentionally reducing the crystallinity significantly below \(R_c \sim 50\%\) and finally to \(R_c = 0\%\) at the end of the intrinsic layer and splitting the intrinsic layer deposition into three sub-layers with \(i_1\), \(i_2\) and \(i_3\) results in increased \(V_{oc}\) and FF values. And finally in a third step a fourth i-layer (\(i_4\)) with medium crystallinity (\(R_c \sim 25–30\%\)) was introduced which further increased the efficiency. Introducing this sophisticated \(R_c\) profile with the different sub-layers enabled to tune solar cell parameters \(J_{sc}\) and \(V_{oc}\) separately with no or only negligible negative impact on the other parameters and finally resulting in additional efficiency gain beyond devices with \(R_c \sim 45–60\% \, \text{“constant”}\) throughout the intrinsic layer.

#### 3.6.3.1. \(i_1\) and \(i_2\) Layer

The \(i_1\)-layer is the starting intrinsic microcrystalline absorber layer tuned for reaching high crystallinity within a minimal layer thickness. To promote crystalline growth and to achieve a highly crystalline sub-layer (\(i_1\)-layer) already after a few tens of nm, SC has to be lowered and/or RF power has to be increased compared to the deposition conditions for the single regime bulk deposition.

Since the ion damage is increasing with RF power [20], only SC...
was varied in an optimization series from 4.2% to 5.8%. The power density of 0.26 W/cm² was kept constant and as a result the optimum SC of 4.6% was found for the i₁-layer. The i₁ thickness was optimized in additional experiments to a value between 150 nm and 200 nm. For the i₂-layer the optimized process parameters with SC=5.8% are similar to the parameters for the single i-layer deposition.

The effect on $R_c$ of the i₁-i₂-layer concept compared to the single i-layer deposition is verified by measuring $R_c$ on two large area “full cell stack” samples both with an intrinsic microcrystalline layer of totally 300 nm in thickness and deposited using the same power density of 0.26 W/cm². The first sample had a 300 nm single i-layer prepared with SC=5.8% and the second sample was prepared with a layer combination of i₁=100 nm and i₂=200 nm fabricated with SC=4.6% and SC=5.8%. After 300 nm of deposition an average $R_c$ of 27% was measured for the single i-layer device whereas the i₁-i₂ layer design reached $R_c=48%$ confirming the effectiveness of the method. Modules prepared using a bottom cell based on 150 nm i₁ and 1350 nm i₂ were compared to modules having a single i-layer of 1500 nm thickness resulting in a 2.3% improvement of power and current density due to an effective reduction of the fraction of material with amorphous characteristics. The other parameters $V_{oc}$ and FF did not change significantly. This increase in current could be achieved alternatively by increasing the thickness of the absorber layer of ~7–10%.

### Table 6.
Summary of i-layer designs and incremental relative improvements of the initial IV parameters of MICROMORPH™ large area modules. $R_c$ was measured at the end of each layer; SC: silane concentration.

<table>
<thead>
<tr>
<th>Design</th>
<th>Single i</th>
<th>i₁-i₂</th>
<th>i₁-i₂-i₃</th>
<th>i₁-i₂-i₂c-i₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>5.8%</td>
<td>4.6–5.8%</td>
<td>4.6–5.8% – 4.9%</td>
<td>4.6–5.5% – 6.7%–4.9%</td>
</tr>
<tr>
<td>Power density (W/cm²)</td>
<td>0.26</td>
<td>0.26–0.26</td>
<td>0.26–0.26–0.13</td>
<td>0.26–0.26–0.13–0.13</td>
</tr>
<tr>
<td>Measured $R_c$</td>
<td>50%</td>
<td>50–60%</td>
<td>50–60% – 0%</td>
<td>50%–60% – 30%–0%</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>100</td>
<td>0.0</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>FF</td>
<td>100</td>
<td>0.0</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>$J_{sc}$</td>
<td>100</td>
<td>2.3</td>
<td>–0.8</td>
<td>–1.4</td>
</tr>
<tr>
<td>$\eta$</td>
<td>100</td>
<td>2.3</td>
<td>1.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

3.6.3.2. i₃ and i₂c Layer. When $R_c$ is decreased from a high crystallinity level the current generation decreases but the open circuit voltage increases as shown in Fig. 8. This behavior is the base of the idea to increase $V_{oc}$ by introducing a low crystallinity sub-layer at the end of the intrinsic i-layer deposition where only a small amount of light is absorbed. The resulting reduced current generation in this layer will have a small negative impact on the efficiency. Results of a series of modules produced maintaining the total i-layer thickness constant but replacing the last part of i₂ with an i₃ layer of increasing thickness prepared using SC=4.9% and a power density of 0.13 W/cm² are shown in Fig. 9. $R_c$ of the i₃ layer measured on the full stack was 0%, e.g. the layer was amorphous. With increasing i₃ thickness from 0 to 300 nm both $V_{oc}$ and FF are constantly increased up to ~1.4% and 1.1% relative. On the contrary $J_{sc}$ is reduced by ~1.4%. A net increase of power by 1.25% is achieved by using an i₁ layer thickness of 200 nm. For the optimum balance of currents of the top and the bottom cell in a MICROMORPH™ device the loss of current caused by introducing i₃ can be compensated by slightly increasing the thickness of i₂.

Up to this point a standard intrinsic bulk layer is separated into three sub-layers i₁/i₂/i₃ with ~200/1100–1400/200 nm in thickness. It is plausible that the i₂ layer with more than a micrometer thickness and $R_c$~45–60% is the most promising candidate for further optimization.

While keeping i₁, i₃ and the total thickness constant, the last 200 nm to 400 nm in thickness of i₂ were replaced by a new sub-layer i₂c where SC for i₂c was changed from 5.8% to 6.7% to reduce the Raman crystallinity onto a moderate level of $R_c$~20–30%. The reduction of $R_c$ was confirmed by measurements done at the end of i₂c on the full stack prepared on a separate substrate. The maximum efficiency gain of 1% was achieved for a 200 nm thick i₂c layer: an increase in $V_{oc}$ of 1.1% and in FF of 1.3% could be realized at the expense of a $J_{sc}$ reduction of 1.4% due to the lowered $R_c$. Again the loss of current generation could be easily compensated by minor adjustments of the remaining i₂ layer thickness.

An overall gain in efficiency of 4.6% relative could be realized by the subdividing the intrinsic absorber into four sub-layers maintaining the total intrinsic absorber layer thickness constant. Table 6 summarizes the contributions to the IV parameters of the layer designs of increasing complexity. Separate tuning of single IV parameters in different volumes of the intrinsic absorber by tuning the Raman crystallinity profile in the range of $R_c$~0–65% and optimizing layer thickness is a new concept for high efficiency microcrystalline solar devices. The final design of the intrinsic µc-Si:H layer of the microcrystalline bottom cell for best efficiency obtained so far, comprises four different sub-layers. The first sub-layer, i₁ with 200 nm in thickness is tuned to quickly reach a high level of $R_c$ to support high current generation. The second sub-layer i₂ with a thickness of 800–900 nm or more is as well dedicated for high current generation maintaining $R_c$ in the transition region of $R_c$~45–60%. The third sub-layer with a 200–800 nm thick i₂c layer (in the world record design i₂c~800 nm) and $R_c$=20–30%, enables a smooth transition from the highly crystalline i₂-layer to the final, amorphous layer with 200 nm in thickness and $R_c=0%$, which is dedicated to boost $V_{oc}$.

![Fig. 9. Initial IV parameters of MICROMORPH™ large area modules starting with a µc-Si:H i-layer design (i₁+i₂+i₃) of 200+i₁+i₂+i₃=1500 nm. The i₁ ($R_c=0%$) thickness is increased while the i₂ thickness is reduced to maintain the total thickness constant, i₁ is kept constant.](image-url)
This cell design was used the 12.34% world record MICRO-MORPH™ module described in [3,4].

4. Conclusions

The intrinsic microcrystalline bulk is the key functional layer in the MICROMORPH™ bottom cell which accounts also for the biggest fraction of the active layers too. High material quality combined with high deposition uniformity, especially significant for large area modules are essential requirements to control and fine-tune the intrinsic absorber and to realize high efficiency microcrystalline and MICROMORPH™ devices. By analyzing and comparing IV parameters of the solar devices and by microscopic analysis of cracks in the intrinsic absorber the material quality can be assessed qualitatively. The material quality was improved significantly by increasing the deposition pressure from 250 Pa to 2000 Pa accompanied by simultaneously reducing the inter-electrode gap distance from 28 mm to 7 mm to prevent powder formation. As an economical side effect the high working pressures enables the deposition of high quality material with high rates and high material utilization.

The common design rule of maintaining Rs of intrinsic absorber in or nearby the transition region in combination with high quality engineering) at EPFL and TEL Solar-Lab SA, Neuchâtel. Electronics and Microtechnology), IMT (Institute of Micro- and exchanges of information with the CSEM (Swiss Centre for Energy Mater. Sol. Cells 144 (2016) 1–95, http://dx.doi.org/10.1016/j.

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References


