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# HIGH-EFFICIENCY AMORPHOUS AND "MICROMORPH" SILICON SOLAR CELLS

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## ABSTRACT

LP-CVD ZnO has been developed at IMT as front TCO for a-Si:H p-i-n single-junction and “micromorph” (microcrystalline/amorphous silicon) tandem solar cells. An amorphous silicon single-junction p-i-n cell (~1 cm$^2$) with a stabilized efficiency of 9.47 % has independently been confirmed by NREL. Applying the monolithic series connection by laser-scribing, both for amorphous single-junction and micromorph tandem cells, modules have been fabricated on LP-CVD ZnO. After light-soaking, mini-modules, with an aperture efficiency of 8.7 % in the case of amorphous silicon cells (confirmed by NREL), and of 9.8 % in the case of micromorph tandem cells, have been obtained. Micromorph tandem cells with an intermediate TCO reflector between the amorphous top and the microcrystalline bottom cell reveal an almost stable performance ($\eta$ = 10.7 %) with respect to light-soaking.

## 1. INTRODUCTION

Light-trapping by transparent conductive oxides (TCO’s) plays a fundamental role for the efficiency of thin-film silicon solar cells. The key factors necessary for a high quality TCO performance are high transparency, high electrical conductivity and high scattering ability. A good TCO layer enhances the optical absorption for amorphous, as well as for microcrystalline silicon, thereby, allowing a reduction of the absorber thickness.

IMT has, therefore, started developing its own "in-house" zinc oxide, prepared by low pressure chemical vapour deposition (LP-CVD) [1-3]. This specific TCO has notable advantages for thin-film solar cells in general. ZnO itself is an abundant, low-cost material. The LP-CVD method is a simple process with deposition rates of over 20 Å/sec making upscaling to areas of 1m$^2$ easily achievable. Furthermore, the LP-CVD process leads to a highly as-grown texturing of the ZnO films. The low process temperatures of around 200 °C are entirely compatible with low-cost substrates (polymers, aluminium,..) and the amorphous silicon PECVD (plasma enhanced chemical vapour deposition) fabrication technology.

In previous studies we have already compared our “in-house” ZnO with the best commercially available $SnO_2$ (Asahi U) applied as front TCO in p-i-n configurated solar cells [4-7]. In this paper we report on the further progress of amorphous and micromorph solar cells using LP-CVD ZnO as front TCO. State-of-the-art mini-module fabrication using the laser-scribing technique for both amorphous single-junction and micromorph tandem cells will be given.

The high photocurrent potential of microcrystalline silicon solar cells can be optimally utilized with the application of an intermediate reflector between the amorphous silicon (a-Si:H) top and the microcrystalline silicon (µc-Si:H) bottom cell. This concept, introduced by IMT in 1996 [8], permits an increase of the a-Si:H top cell current and allows hence a reduction of the top a-Si:H cell thickness to improve the stability of the tandem cell. By applying this intermediate TCO reflector concept, Yamamoto et al [9, 10] have recently demonstrated an initial cell efficiency of 14.5 %.

Such “modified” micromorph tandem cells have been also investigated by IMT.

## 2. EXPERIMENTAL

The deposition of LP-CVD ZnO layers has been described in previous studies [1-3]. As substrate AF45 Schott glass was used. The a-Si:H p-i-n and micromorph a-Si:H/µc-Si:H tandem solar cells were fabricated by VHF-PECVD (Very High Frequency) in a 8x8 cm$^2$ substrate size laboratory reactor. The deposition rates for both the amorphous and the microcrystalline intrinsic layers is around 5 Å/s. The laser-scribing technique was applied for the preparation of test cells and mini modules. In order to avoid peripheral collection effects well-defined test cells of around 1 cm$^2$ were scribed by the 532 nm laser. Mini modules applying the integrated series connection by laser scribing [11] were prepared both for amorphous single-junction and micromorph tandem devices. The cells and modules were characterised using an AM1.5 sun simulator (Wacom WXS-140S-10), and test cells were additionally analysed by quantum efficiency measurements. Amorphous silicon single-junction p-i-n cells and modules were independently characterised by NREL (National Renewable Energy Laboratory, USA).

The degradation of test cells and modules was performed under AM1.5 close conditions (1 sun intensity and 50 ˚C device temperature).

## 3. RESULTS AND DISCUSSION

### 3.1 Amorphous silicon p-i-n test cells

Recently, we reported [4] on high stable efficiencies of 9 % for a-Si:H p-i-n cells when applying LP-CVD ZnO as front TCO. As IMT holds in-house now the full cell and module fabrication technology, light-incoupling can be additionally improved by applying an antireflective (AR) coating. Therefore, on the front glass side a broadband AR-coating was applied. Figure 1 shows the effect of the AR-coating on the reflectivity of amorphous p-i-n cells in comparison with non-coated substrates of LP-CVD ZnO and $SnO_2$ (U-type) from Asahi Glass. While already ZnO shows a reduced reflectance compared to $SnO_2$ the AR-coating in combination with ZnO allows to further reduce the reflectance.

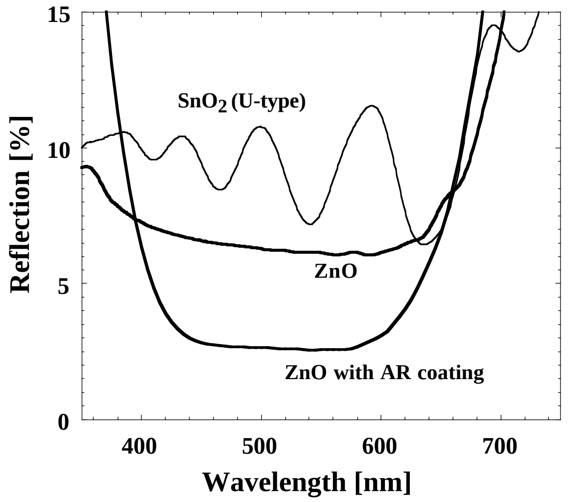
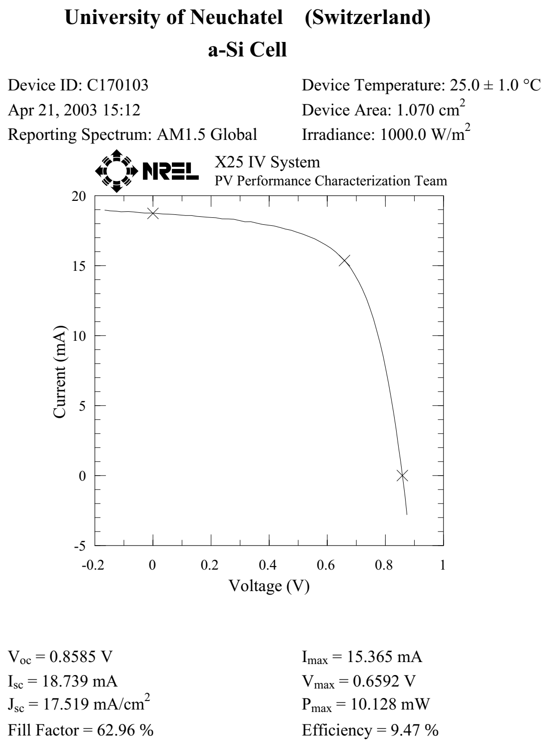


Fig. 1: Comparison of the reflectivity of amorphous p-i-n cells deposited on $SnO_2$ (Asahi U), on LP-CVD ZnO and on LP-CVD ZnO substrates clad with an antireflective (AR) coating. Note the reduced reflectance of only 2.5-2.6 % in the important absorption range of the solar cell.



**University of Neuchatel (Switzerland)**

**a-Si Cell**

| | |
|---|---|
| Device ID: C170103 | Device Temperature: 25.0 ± 1.0 °C |
| Apr 21, 2003 15:12 | Device Area: 1.070 $cm^2$ |
| Reporting Spectrum: AM1.5 Global | Irradiance: 1000.0 $W/m^2$ |

| | |
|---|---|
| $V_{oc}$ = 0.8585 V | $I_{max}$ = 15.365 mA |
| $I_{sc}$ = 18.739 mA | $V_{max}$ = 0.6592 V |
| $J_{sc}$ = 17.519 $mA/cm^2$ | $P_{max}$ = 10.128 mW |
| Fill Factor = 62.96 % | Efficiency = 9.47 % |

Fig. 2: NREL AM1.5 I-V characteristics of an amorphous p-i-n single-junction solar cell deposited on LP-CVD ZnO coated glass after light-soaking of 800 h. The front of the glass substrate is covered by a broadband AR-coating (see Fig. 1).

Amorphous p-i-n cells were fabricated on AR-coated ZnO glass substrates and were afterwards light-soaked. Such a cell was independently characterized by NREL. Figure 2 shows the I-V characteristics under AM1.5 illumination of a cell having a stabilized efficiency of 9.5 %. This p-i-n cell has an i-layer thickness of only ~0.25 µm and reveals a very high stabilized short-circuit-current density ($J_{sc}$) of over 17.5 $mA/cm^2$ (initial > 18 $mA/cm^2$).

The spectral analyse of the photocurrent in Fig. 3 (measurement done by NREL) attributes the AR-coated cell a high quantum efficiency even in the degraded state. The QE reaches a level of remarkable 94 % in the important part of the cell absorption supporting the high transparency and photocurrent potential of LP-CVD ZnO as front TCO. The independently confirmed efficiency of 9.47 % is to our knowledge the highest efficiency ever reported for stabilized single-junction a-Si:H devices [12].

In Fig. 4 the stabilisation of this record cell is given in function of the light exposure time. The typical relative degradation of cells of such thickness is about 15 %.

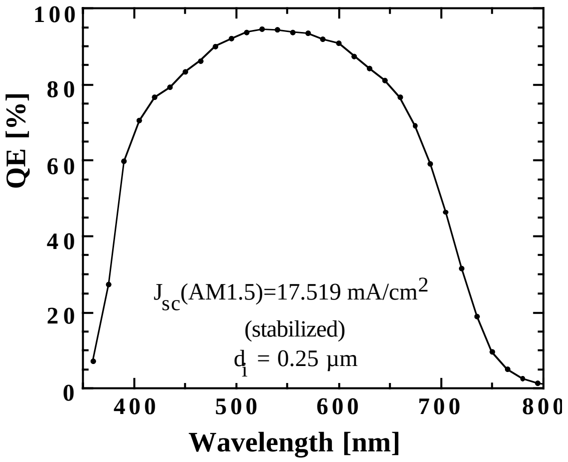


Fig. 3: Quantum efficiency of the light-soaked 9.5 % efficiency p-i-n solar cell of Fig. 2 and 4 (measured by NREL).

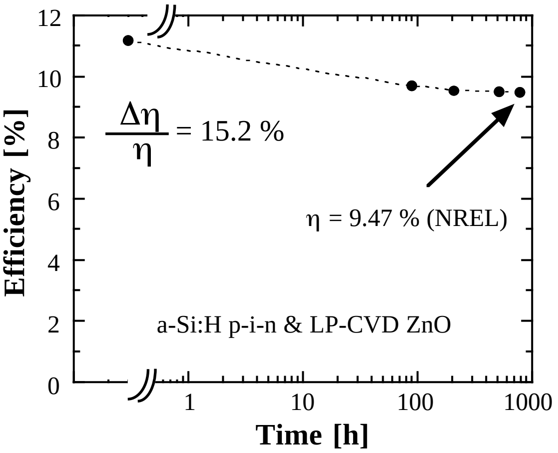


Fig. 4: Light-soaking performance of the a-Si:H p-i-n cell in Fig. 2&3. The stability check is performed under 1 sun AM1.5 close conditions and 50 °C cell temperature. This cell was sent to NREL after 800 h of light-soaking.

### 3.2 Micromorph silicon tandem test cells

Micromorph (a-Si:H/µc-Si:H pin/pin) tandem cells have been as well fabricated on in-house LP-CVD ZnO as front TCO. Hereby, the µc-Si:H bottom cells have a thickness in the range of 1.8 to 2 µm, whereas the top cells in the order of 0.25 µm. Figure 5 shows that high initial efficiencies of over 12 % could be achieved, leading to high open circuit voltages of 1.4 volts. After light-soaking (1000 h) these cells show stabilized efficiencies of 10.8 %.

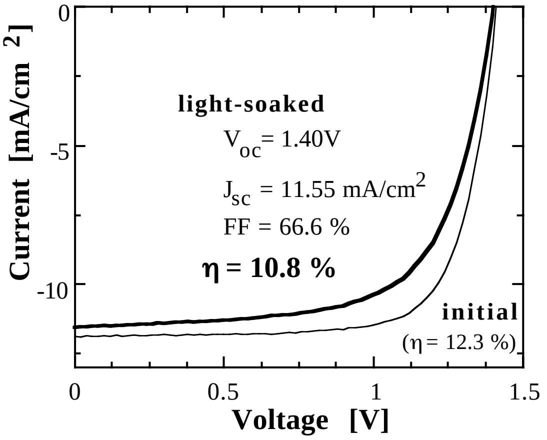


Fig. 5: I-V characteristics (AM1.5) of a micromorph tandem test cell on LP-CVD ZnO in the initial state and after 1000 h of light-soaking (1 sun @ 50 ºC). The µc-Si:H bottom cell has a thickness of 2 µm.

### 3.3 Intermediate reflector in micromorph tandem cells

Recently, Yamamoto et al. [9, 10] have demonstrated that applying the concept of the intermediate TCO reflector allows to enhance the initial cell efficiency of micromorph tandem cells beyond the 14 % limit. The TCO layer between the amorphous top and the microcrystalline silicon cell increases the a-Si:H top cell photocurrent remarkably. Or contrary, this intermediate TCO layer allows to reduce the top cell thickness while maintaining a high top photocurrent. A reduced top cell thickness has in addition the advantage of a better stability. The impact of an intermediate TCO layer on the QE of top and bottom cells is given in Fig. 6. Top cells of 0.18 µm thickness can easily achieve similar photocurrents than top cells in micromorph tandems without internal TCO layers of 0.25 µm thickness. However, the bottom cell photocurrent is reduced, but still at a µc-Si:H bottom cell thickness of 2 µm short-circuit current densities of over 11 mA/cm$^2$ can be achieved. This concept allows a better stability at comparable overall cell thickness. Figure 7 shows the AM1.5 I-V characteristics of our most recent tandem cell with an intermediate TCO reflector incorporated leading hereby to an initial cell efficiency of 11.1 %. Of course the stability under light-soaking has to be checked of each such new device, however, our sofar fabricated micromorph tandems with intermediate reflectors reveal a surprisingly high stability. As Table I reflects, there is no significant change in I-V characteristics of a cell of a generation before after a period of even over 1300 h prolonged light-soaking.

As the tandem cell in Table I is bottom limited and as it consists of a very thin a-Si:H top cell (<0.2 µm) the fill factor is principally given by the stable µc-Si:H bottom cell and is therefore less influenced by small alterations in the a-Si:H top cell (by light-induced degradation).

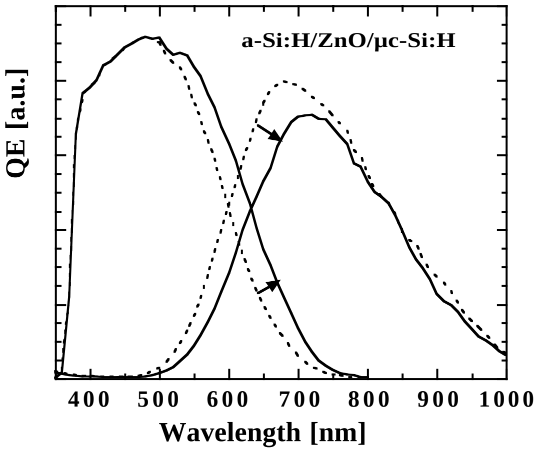


Fig. 6: Effect of the intermediate TCO layer on the quantum efficiency of the a-Si:H top and µc-Si:H bottom cells. The dashed lines represent the tandem without the interlayer, the solid lines the one with an intermediate ZnO layer.

Our own experiments with the intermediate TCO layer reveals the potential of high top cell photocurrents of over 14 mA/cm$^2$ as demonstrated by Yamamoto et al. [9, 10], however, the µc-Si:H bottom cell thickness has to be increased beyond 2 µm to balance AM1.5 current matching. Further investigations on different tandem cells with intermediate TCO layers need to be done to explore the full efficiency potential of the micromorph thin film silicon solar cells. Hereby, the main question is to what extent the efficiency of micromorph tandem cells with intermediate TCO reflectors can be improved while keeping the µc-Si:H bottom cell thin enough.

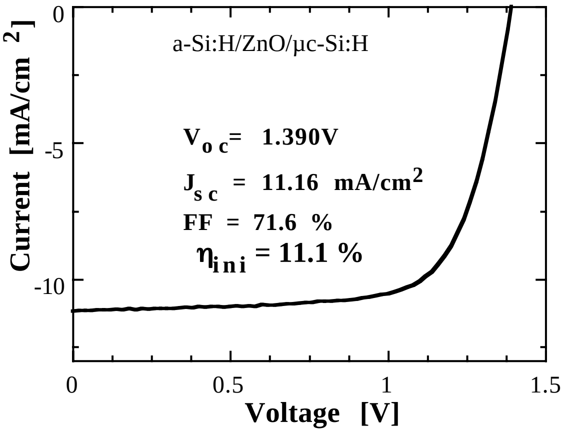


Fig. 7: AM1.5 I-V characteristics of IMT's most recent micromorph tandem cell with intermediate ZnO layer incorporated (initial state).

Table I: Micromorph tandem cell with an intermediate ZnO layer in the initial state and after 1300 h of light-soaking.

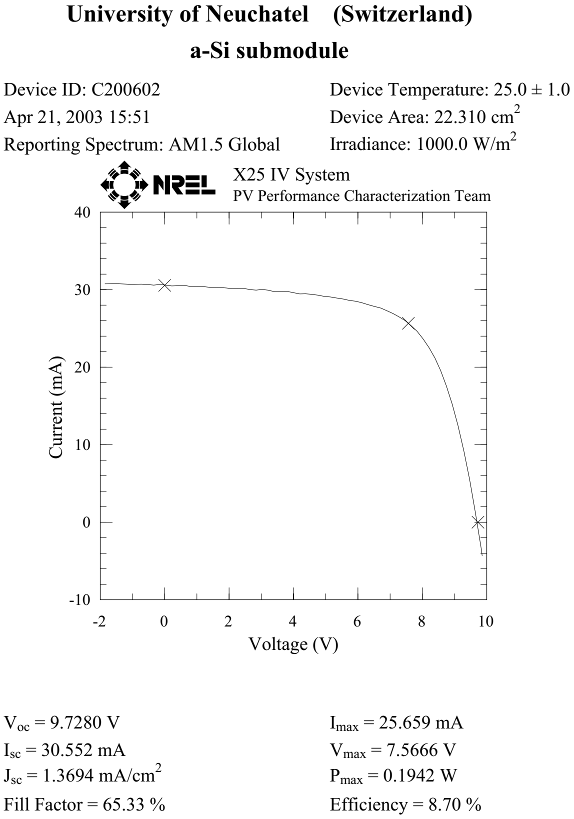
| cell state | $V_{oc}$ (V) | FF (%) | $J_{sc}$ (mA/cm$^2$) | η (%) |
|---|---|---|---|---|
| initial | 1.378 | 73.6 | 10.5 | 10.65 |
| light-soaked | 1.418 | 72.1 | 10.5 | 10.73 |

### 3.4 Amorphous silicon modules

Laser-patterned LP-CVD ZnO glass substrates have been used for the deposition of amorphous single-junction cells for the fabrication of “entirely” amorphous mini-modules, with integrated monolithic series connection.

Fig. 8 shows the AM1.5 I-V characteristics of a 11-segmented module with 22.31 $cm^2$ aperture area in the stabilized state (1000 h of light-soaking). The measurement has independently been performed at NREL and confirms a high stable module efficiency of 8.7 %. The result of Fig. 8 shows that a high quality front TCO as in case of LP-CVD ZnO opens a new efficiency potential for this simple amorphous silicon device. The a-Si:H single-junction p-i-n solar cell and an efficient light-trapping may lead to as high module efficiencies as sophisticated multi-junction devices based on amorphous silicon and expensive silicon-germanium alloys. Moreover, the manufacturing of such single-junction cells is less complicated and delicate than very thin multi-junction solar cells with its many interfaces. This simplification in mass production should lead to reduced manufacturing costs ($\$/W_p$).

As the dead scribe area loss of the module in Fig. 8 is about 3 %, the 8.7 % module efficiency is in agreement to our earlier results of a stable 9 % test cell technology for a-Si:H p-i-n cells (without AR-coating) and LP-CVD ZnO [4].



**University of Neuchatel (Switzerland)**

**a-Si submodule**

Device ID: C200602 Device Temperature: 25.0 ± 1.0

Apr 21, 2003 15:51 Device Area: 22.310 $cm^2$

Reporting Spectrum: AM1.5 Global Irradiance: 1000.0 $W/m^2$

$V_{oc}$ = 9.7280 V $I_{max}$ = 25.659 mA

$I_{sc}$ = 30.552 mA $V_{max}$ = 7.5666 V

$J_{sc}$ = 1.3694 $mA/cm^2$ $P_{max}$ = 0.1942 W

Fill Factor = 65.33 % Efficiency = 8.70 %

Fig. 8: AM1.5 I-V characteristics of a 11-segmented a-Si:H p-i-n single-junction module based on LP-CVD ZnO as front TCO (without AR coating). The module was light-soaked for 1000 h (1 sun @ 50 °C). The efficiency of 8.7 % is confirmed by NREL.

### 3.5 Micromorph mini-modules

Micromorph p-i-n/p-i-n tandem cell modules have been fabricated on glass substrates coated with LP-CVD ZnO as well. The AM1.5 I-V characteristics of a 9-segmented module in the initial and light-soaked state (after 1000 h) are given in Fig. 9.

The module shows initially an efficiency of 11 %, a fact that confirms the high quality of the developed series interconnection. After light-soaking a stabilized aperture efficiency of 9.8 % could be obtained.

A further improvement in the micromorph module is now clearly linked with an appropriate choice of the amorphous top cell implemented.

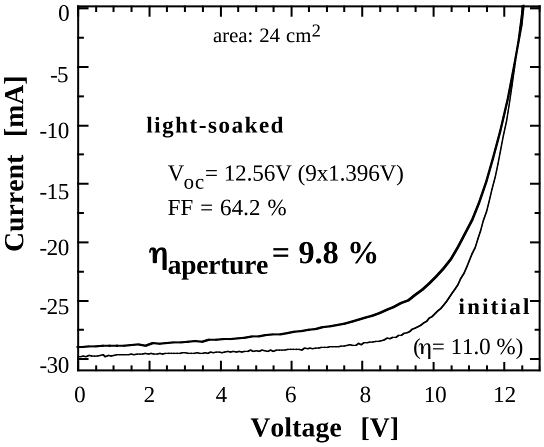


Fig. 9: AM1.5 I-V characteristics of a micromorph tandem cell module fabricated on LP-CVD ZnO-coated glass in the initial and light-soaked state. The µc-Si:H bottom cell has a thickness of 2 µm.

### 4. CONCLUSIONS

Light-trapping plays a dominant role in achieving high efficiencies of thin film silicon solar cells. As shown in this study LP-CVD ZnO applied as front-TCO has excellent light-confinement properties allowing for high solar cell efficiencies. In case of an amorphous silicon single-junction p-i-n solar cell a stabilized record efficiency of 9.47 % could be attained and independently confirmed by NREL. This result could be achieved thanks to the application of a broadband antireflective coating on the front glass side. Quantum efficiency data reveal excellent light-trapping leading to QE-values of 94 % in the important absorption range even in the stabilized state of the single-junction p-i-n solar cell. In case of in-house fabricated mini-modules with series interconnected a-Si:H single-junction cells a stabilized aperture module efficiency of 8.7 % could be obtained as well and independently confirmed by NREL.

These results suggest that the combination of a high-quality TCO with a single-junction amorphous silicon cell allows a simplification of module manufacturing while sustaining a high efficiency at reduced process time and costs. LP-CVD ZnO in combination with a simple single-junction deposition technology is a strong candidate to bring the cost of PV (in $\$/W_P$) down. The gain in efficiency due to an efficient AR-coating has to be balanced with the additional costs involved.

In connection with micromorph tandem cells, the use of LP-CVD ZnO enables the reduction of the µc-Si:H bottom cell thickness to 2 µm while maintaining a high efficiency of 12.3 % in the initial and 10.8 % in the light-soaked state. A successful implementation of the monolithic series connection by laser-scribing and the use of LP-CVD ZnO in micromorph tandem cells resulted in an aperture area module efficiency of initially 11 % and stabilized 9.8 %. By improving both types of cells and by perfecting the series interconnection, we should be able to obtain a further increase in module efficiency.

Micromorph tandem test cells with intermediate ZnO reflector layers between the amorphous top and microcrystalline bottom cell reveal a high stability under prolonged light-soaking. We obtained already a high stable efficiency of 10.7 %, with a µc-Si:H bottom cell thickness of 1.8 µm. Our most recent micromorph tandem test cell with intermediate ZnO reflector resulted in an initial efficiency of 11.1 %. This result could be obtained at a top cell thickness of 0.18 µm and a µc-Si:H bottom cell of only 2 µm. A further improvement to values above 12 % is foreseeable at reasonable cell thicknesses.

Low-cost, high-quality TCO layers and economical mass-production fabrication processes (such as LP-CVD ZnO and VHF-PECVD) are applicable today in thin-film silicon modules; they are essential for the reduction for the high costs associated with PV. Using LP-CVD ZnO amorphous single-junction and micromorph tandem solar cells with the highly reliable glass/TCO/p-i-n configuration will definitely lead in the near future to the production of modules with reasonably high stabilized efficiencies (around 8 % or around 10 %, respectively, for the single-junction and for the tandem case); thereby, this very same combination will allow for significant reductions in deposition process times and in material costs, leading, thus, to attractively low costs for module manufacturing (1 $\$/W_p$ becomes a realistic and attainable value).

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