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Potential of amorphous and microcrystalline silicon solar cells

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Abstract

Low pressure chemical vapour deposition (LP-CVD) ZnO as front transparent conductive oxide (TCO), developed at IMT, has excellent light-trapping properties for a-Si:H p-i-n single-junction and 'micromorph' (amorphous/microcrystalline silicon) tandem solar cells. A stabilized record efficiency of 9.47% has independently been confirmed by NREL for an amorphous silicon single-junction p-i-n cell ($\sim$1 cm^2) deposited on LP-CVD ZnO coated glass. Micromorph tandem cells with an initial efficiency of 12.3% show after light-soaking a stable performance of 10.8%. The monolithic series connection by laser-scribing for module fabrication has been developed at IMT as well, for both amorphous single-junction and micromorph tandem cells in combination with the LP-CVD ZnO technique. Mini-modules (areas between 22 and 24 cm^2) with an aperture efficiency of 8.7% in the case of amorphous single-junction p-i-n cells (independently confirmed by NREL), and of 9.8% in the case of micromorph tandem cells, have been obtained. Micromorph tandem cells with an intermediate TCO reflector between the amorphous top and the microcrystalline bottom cell show an almost stable performance ($\eta = 10.7\%$) with respect to light-soaking.
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Keywords: Amorphous silicon; Microcrystalline silicon; Thin-film silicon solar cells; Light-trapping; LP-CVD ZnO; VHF-PECVD

1. Introduction

The capability of light-trapping of transparent conductive oxides (TCOs) is fundamental for the efficiency of thin-film silicon solar cells. A high transparency, a high electrical conductivity and a high scattering ability are necessary material parameters of a high quality TCO. Owing to a good TCO layer the effective optical absorption for amorphous (a-Si:H), as well as for microcrystalline silicon (μc-Si:H), can be significantly increased, thereby, allowing a reduction of the absorber thickness. In the case of amorphous silicon, this advantage leads to an improved stability, and in the case of microcrystalline silicon to a reduction of the deposition time.

The key role of the TCO for thin-film solar cells was the motivation for IMT to develop its own 'in-house' TCO, namely ZnO, prepared by the low pressure chemical vapour deposition (LP-CVD) technique [1–3]. This particular TCO has notable advantages for thin-film solar cells in general. ZnO itself is an abundant and low-cost material. The LP-CVD deposition technique is a simple process with deposition rates of over 2 nm/s making upscaling to areas of 1 m^2 easily achievable. In addition, the LP-CVD process leads directly to an as-grown high surface texturing of the ZnO films. Furthermore, the involved low process temperatures of approximately 200 °C are entirely compatible with low-cost substrates (inexpensive glass, polymers, aluminium, stainless steel, etc.) and the a-Si:H plasma enhanced chemical vapour deposition (PECVD) fabrication technique.

In previous studies we have already compared our 'in-house' ZnO with the best commercially available SnO_2 (Asahi U) in p-i-n configurated solar cells, both amorphous single-junction and micromorph tandem devices [4–7]. In this paper we report on the further progress of amorphous and micromorph solar cells applying LP-CVD ZnO as front TCO. Due to the excellent light-trapping of ZnO the main focus was to reduce the absorber thickness, while keeping a high efficiency potential. In combination with LP-CVD ZnO, as front TCO, the laser-scribing patterning for mini-modules has been developed for both the very thin amorphous single-junction and the thicker micromorph

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tandem cells. The performance of state-of-the-art mini-modules will be given.

In 1996 IMT introduced, the concept of an intermediate reflector between the amorphous top and microcrystalline bottom cell [8]. This concept permits an increase of the a-Si:H top cell photocurrent due to the difference in the refraction index of the interlayer and the silicon absorbers. Thanks to the high infrared photocurrent potential of the microcrystalline bottom cell a balance of the gained a-Si:H top cell current can principally be achieved by increasing the μc-Si:H cell thickness. Applying this intermediate reflector layer concept, Yamamoto et al. [9–11] have recently demonstrated a notable initial efficiency of 14.7% for a test cell. Conversely, this interlayer allows a reduction of the a-Si:H top cell thickness while maintaining markedly high photocurrents, accordingly improving the overall stability of the tandem cell. Results of such 'modified' micromorph tandem cells obtained by IMT are, also, given in this paper.

2. Experimental

As front glass substrate AF45 Schott glass was used with a thickness of 0.7 mm. The deposition and fabrication of LP-CVD ZnO layers has been described and reported in previous studies [1–3]. The ZnO layers used have a thickness of approximately 2.2 μm and result in a sheet resistance of 6–8 Ω/sq. For the optical properties of the applied ZnO films we refer to earlier work [4,5,7]. The a-Si:H p-i-n and micromorph a-Si:H/μc-Si:H tandem solar cells were fabricated by very high frequency (VHF)-PECVD in a 8×8 cm^2 substrate size laboratory reactor. The deposition rates for both the amorphous and the microcrystalline intrinsic layers is approximately 0.5 nm/s. The principle of the a-Si:H p-i-n cell fabrication, as developed by VHF-PECVD at IMT, is given in detail in earlier publications ([12,13] and references therein).

The patterning of test cells and the series interconnection for the modules was done by the laser-scribing technique [14]. To avoid peripheral carrier collection well-defined test cells were cut by the laser of 532 nm wavelength to an area of approximately 1 cm^2. We have observed that such well-defined cells are quite representative for the extrapolation of expected J_{sc}-values in the case of larger-size modules. The solar cells and modules were characterised using an AM1.5 Global sun simulator (Wacom WXS-140S-10). In addition, test cells were analysed by quantum efficiency (QE) measurements. The light-soaking of cells and modules was performed under AM1.5 close illumination (1 sun intensity and 50 °C device temperature) and open circuit conditions. After the light-soaking experiments amorphous silicon single-junction p-i-n cells and modules were sent to

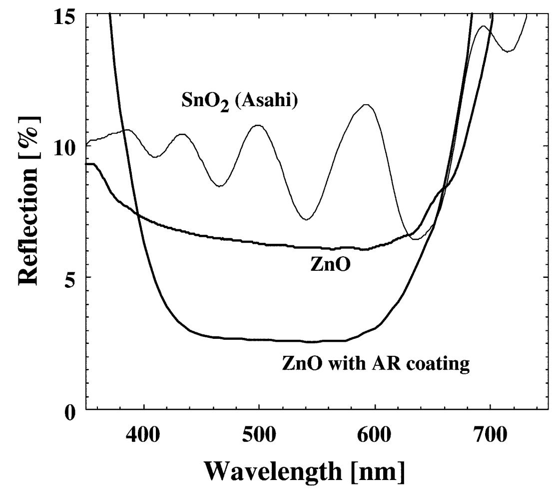

Fig. 1. Comparison of the reflection behaviour (from the glass side) of amorphous p-i-n cells deposited on SnO_2 (Asahi U), on LP-CVD ZnO and on LP-CVD ZnO with an AR-coating. The AR reduces the reflectance by approximately 4%.

NREL (National Renewable Energy Laboratory, USA) for independent AM1.5 I–V and QE characterisation.

3. Results and discussion

3.1. Amorphous silicon p-i-n cells

In a recent study we reported on the achievement of high stable efficiencies of 9% for a-Si:H p-i-n cells when applying LP-CVD ZnO as front TCO [4]. Due to the possibility of keeping the full cell and module fabrication technology at IMT, we are able to additionally improve the light-in coupling by applying an anti-reflective (AR) coating. Consequently, before the ZnO and cell deposition, the front glass side was coated with a broadband AR-layer. Such AR-coatings are widely applied in the glass industry [15]. It consists of a multi-layer design: glass/A/B/A/B ($A=TiO_2$ or Nb_2O_5, $B=SiO_2$). Fig. 1 reveals the impact 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 reported in a previous publication [4]. While ZnO already results in a reduced reflectance compared with SnO_2, the AR-coating in combination with ZnO allows, as expected, a further reduction. Thus, the reflection loss reaches very low values of only 2.5–2.6% in the important absorption spectrum of the a-Si:H p-i-n cell. The part of the remaining 2.5–2.6% is mainly due to the reflection at the glass/ZnO interface as the spectral analysis of the AR-coated glass substrate alone reveals.

Amorphous p-i-n cells prepared on AR-coated ZnO glass substrates were sent after light-soaking to NREL for independent characterisation. Fig. 2 independently confirms the I–V characteristics under AM1.5 illumi-

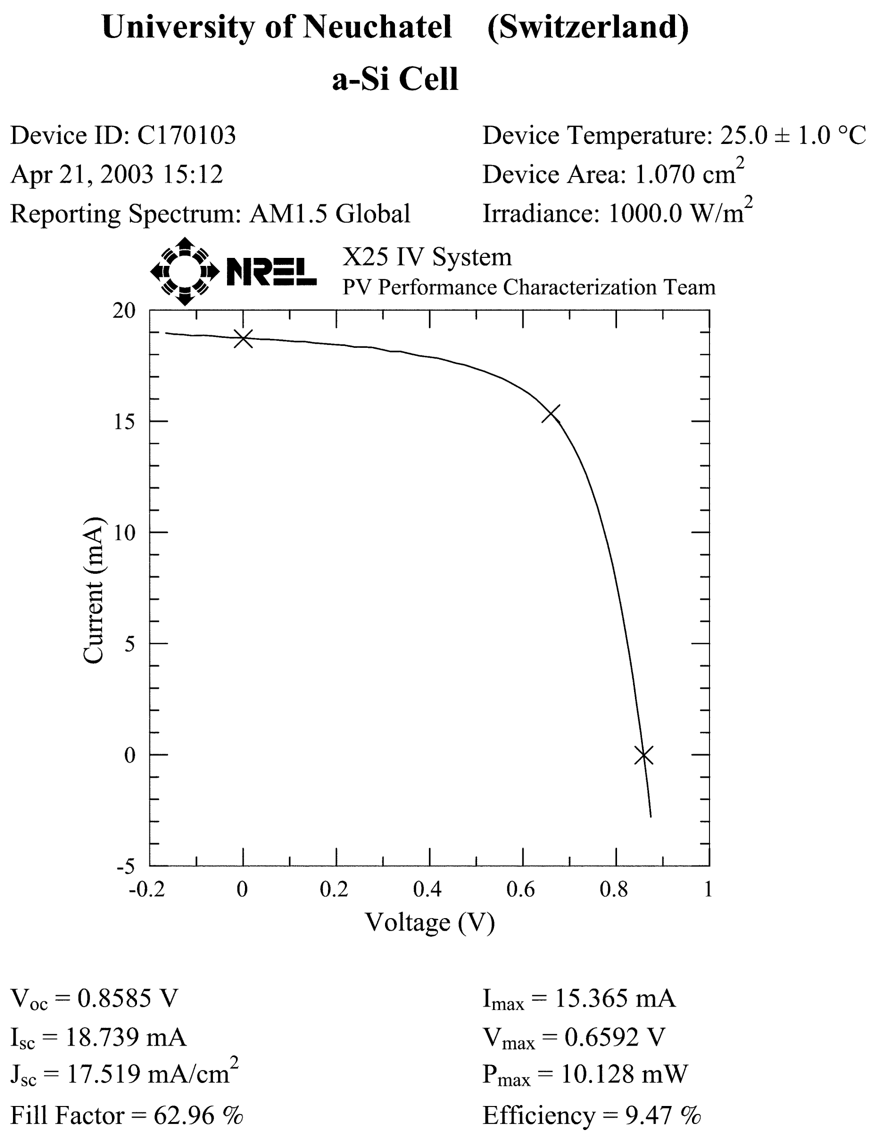

Fig. 2. *I–V* characteristics as measured by NREL of an a-Si:H p-i-n solar cell deposited on LP-CVD ZnO coated glass after light-soaking of 800 h. The glass substrate is covered on the front side by a broadband AR-coating as given in Fig. 1.

nation of a cell having a stabilized efficiency of 9.47%. This p-i-n cell has an i-layer thickness of only ~0.25 μm and reveals a very high level for the stabilized short-circuit-current density (J_{sc}) of over 17.5 mA/cm^2 (initial >18 mA/cm^2). The cell showed an initial efficiency of 11.2% (measured by IMT, unconfirmed) before light-soaking.

The spectral analysis of the photocurrent in Fig. 3 (measurement done by NREL) of the AR-coated cell, shows a high QE even in the degraded state. The QE-values reach a remarkable level of 94% in the important part of the cell absorption. This fact indicates a high transparency, and a high light-trapping capacity for LP-CVD ZnO as front TCO resulting in high photocurrents. The efficiency of 9.47% is to our knowledge the highest independently confirmed for stabilized single-junction a-Si:H devices [16].

In Fig. 4 the stabilization of this record cell is given in function of the light-soaking time. The typical relative degradation of cells having such a thickness is approximately 15%, as previously reported [5].

3.2. Micromorph silicon tandem cells

Micromorph (a-Si:H/μc-Si:H pin/pin) tandem cells have been as well fabricated on LP-CVD ZnO as front TCO. The thickness of the μc-Si:H bottom cells were in the range of 1.8–2 μm, whereas the top cells in the order of 0.25 μm. Fig. 5 shows for the tandem cell a high initial efficiency of over 12% combined with a

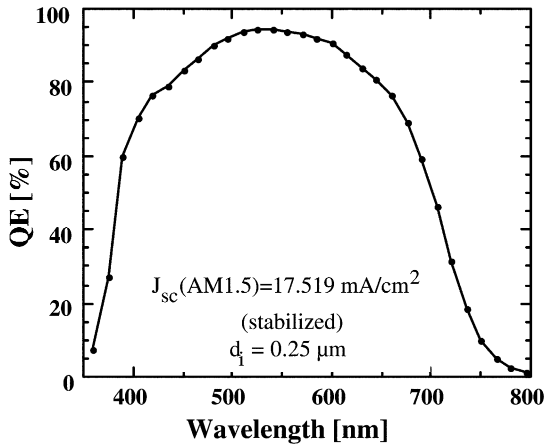

Fig. 3. QE of the light-soaked 9.47% efficiency a-Si:H p-i-n solar cell of Figs. 2 and 4 (measurement by NREL).

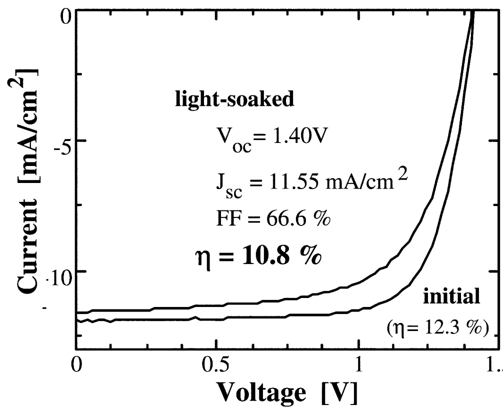

Fig. 5. AM1.5 *I–V* characteristics of a micromorph tandem test cell deposited on glass/LP-CVD ZnO in the initial state and after 1000 h of light-exposure (1 sun at 50 °C). The µc-Si:H bottom cell has a thickness of 2 µm.

high open circuit voltages of 1.4 V. After the light-soaking stability test an efficiency of 10.8% could be measured.

3.3. Intermediate reflector in micromorph tandem cells

As already mentioned, Yamamoto et al. [9–11] have demonstrated that the concept of an intermediate reflector layer allows for an enhancement of the initial cell efficiency of micromorph tandem cells, close to 15%. IMT has observed that the intermediate layer between the amorphous top and microcrystalline silicon bottom cell allows an increase in the a-Si:H top cell photocurrent, at the cost of a reduction in the photocurrent of the µc-Si:H bottom cell. Nevertheless, the intermediate TCO layer allows a reduction of the top cell thickness while keeping a high top photocurrent. A reduced top cell thickness, though, has 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 a-Si:H cells of 0.18 µm thickness can easily achieve similar photocurrents to top cells of 0.25 µm thickness without internal TCO layers applied. However, as in our case, the bottom cell photocurrent is reduced. Nonetheless, at a µc-Si:H bottom cell thickness of 2 µm short-circuit-current densities of over 11 mA/cm^2 can be achieved. The primary potential of this concept is improved stability for comparable overall absorber cell thickness. Fig. 7 gives the AM1.5 *I–V* characteristics of our most recent tandem cell with an intermediate TCO reflector applied leading to an initial efficiency of 11.1%. The stability under light exposure of each new device needs to be checked; however, our fabricated micromorph tandems with intermediate reflectors reveal a surprisingly high stable performance. As Table 1

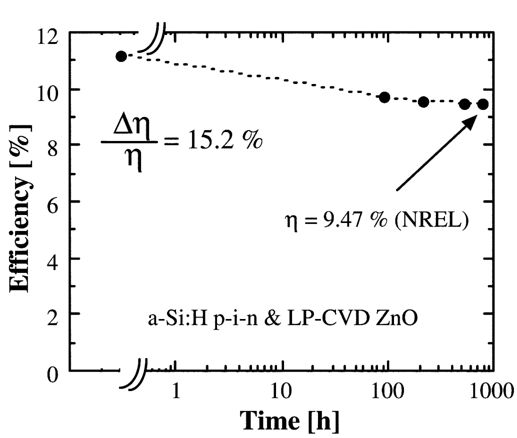

Fig. 4. Light-soaking performance of the a-Si:H p-i-n cell in Figs. 2 and 3. The stability experiment was performed under 1 sun AM1.5 close conditions and 50 °C cell temperature. After 800 h of light exposure the cell was sent to NREL for independent characterisation.

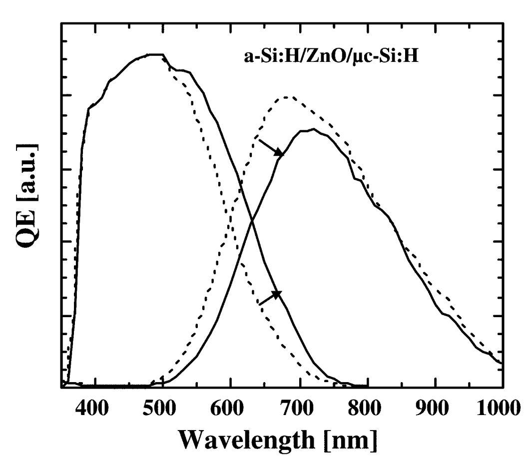

Fig. 6. Impact of the intermediate TCO layer on the QE of the a-Si:H top and µc-Si:H bottom cells. The dashed lines show the tandem without the interlayer, the solid lines represent the one with the incorporated intermediate TCO layer.

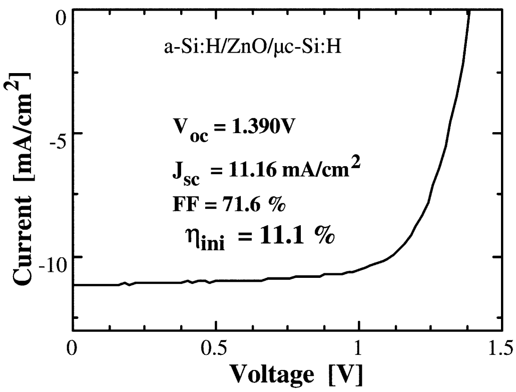

Fig. 7. *I–V* characteristics under AM1.5 of IMT's most recent micromorph tandem cell with intermediate ZnO layer (initial state).

reflects, there is no significant change in *I–V* characteristics of a cell of a previous generation after a period of over 1300 h prolonged light-soaking.

As the micromorph tandem cell in Table 1 is bottom-limited, and as the a-Si:H top cell is in this case very thin (<0.2 μm), the fill factor is principally given by the stable μc-Si:H bottom cell and is, therefore, less influenced by small light-induced alterations in the a-Si:H top cell.

Our own experiments with the intermediate TCO layer reveal the potential of high top cell photocurrents of over 14 mA/cm^2 as demonstrated by Yamamoto et al. [9–11]. The μc-Si:H bottom cell thickness has, however, in our opinion, to be increased beyond 2 μm to balance such high AM1.5 photocurrents. Further investigations on tandem cells with different intermediate layers need to be completed in order to explore the full efficiency potential of the micromorph thin-film silicon solar cells. The chief question is to what extent the efficiency of micromorph tandem cells with intermediate reflectors can be enhanced while keeping the μc-Si:H bottom cell sufficiently thin.

3.4. Amorphous silicon modules

In order to prepare modules with integrated monolithic series connection, laser-patterned LP-CVD ZnO glass substrates have been used for the deposition of amorphous single-junction p-i-n cells. Fig. 8 gives 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 highly stable module efficiency of 8.7%. The result of Fig. 8 shows that a high quality front TCO as in case of IMT's LP-CVD ZnO can lead to a high efficiency potential even for a simple device like the a-Si:H p-i-n cell. With respect to mass production the concept of the a-Si:H single-junction p-i-n solar cell and an efficient light-trapping may lead to high module efficiencies as sophisticated multi-junction devices based on amorphous silicon and expensive silicon–germanium alloys. Moreover, the manufacturing aspect of such single-junction cells seems to be less delicate compared to very thin multi-junction solar cells with their many interfaces and tuned absorber thicknesses. In terms of mass production, this simplification should reduce the manufacturing costs for the modules ($\$/W_p$).

Table 1
Micromorph tandem cell with an intermediate ZnO layer between the a-Si:H top and μc-Si:H bottom cell 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

The bottom cell has a thickness of only 1.8 μm.

As the dead scribe area loss of the module in Fig. 8 is approximately 3%, the 8.7% module efficiency accords with 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].

The characteristic degradation performance of such an a-Si:H module is represented in Fig. 9 in the function of prolonged light-exposure and correlates well with the ones of a-Si:H p-i-n test cell devices (Fig. 4).

3.5. Micromorph tandem modules

Micromorph p-i-n/p-i-n tandem cell modules in combination with LP-CVD ZnO as front TCO have been fabricated. The AM1.5 *I–V* characteristics of a 9-segmented module in the initial and light-soaked state (after 1000 h) are shown in Fig. 10.

The module has in the initial state an aperture efficiency of 11% that confirms the high quality of the

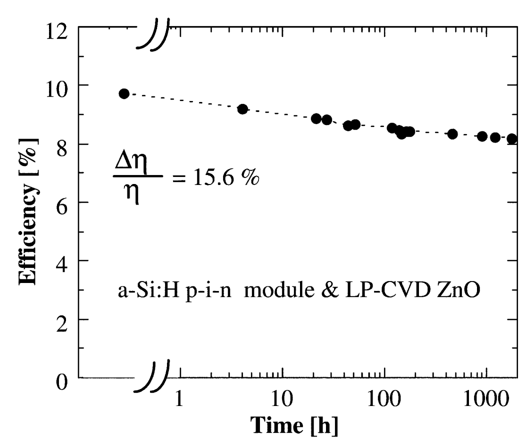

Fig. 8. Typical light-soaking behaviour of an amorphous p-i-n single-junction mini-module under 1 sun AM1.5 close illumination conditions and 50 °C cell temperature.

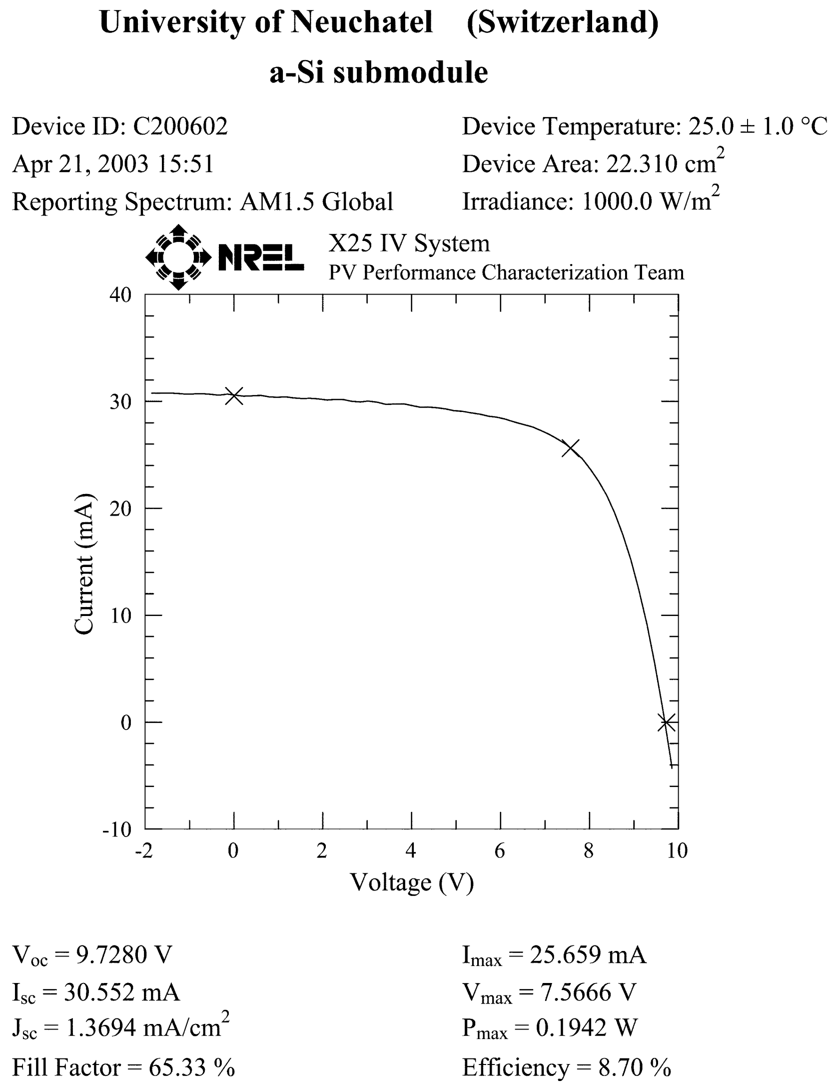

Fig. 9. *I–V* characteristics (AM1.5) as measured by NREL of an 11-segmented a-Si:H p-i-n single-junction module with LP-CVD ZnO as front TCO (without AR-coating). The module was light-soaked for 1000 h (1 sun at 50 °C). The i-layer has a thickness of 0.25 μm.

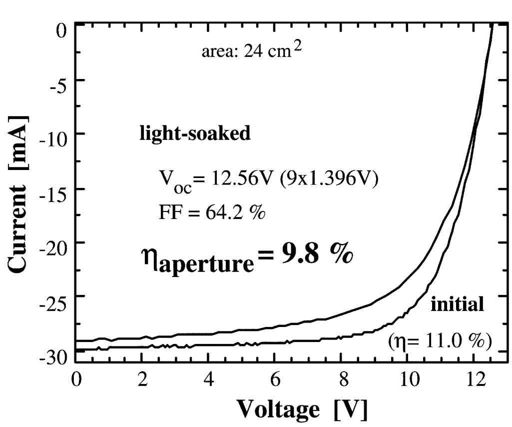

Fig. 10. *I–V* characteristics (AM1.5) of a micromorph tandem cell module fabricated on LP-CVD ZnO-coated glass in the initial and light-soaked state (1000 h under 1 sun and 50 °C). The μc-Si:H bottom cell has a thickness of 2 μm.

developed series interconnection. After light-soaking a stabilized module efficiency of 9.8% has been obtained.

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

4. Conclusions

Light-trapping plays a significant role in achieving high efficiencies of thin-film silicon solar cells. As demonstrated in this study LP-CVD ZnO applied as front-TCO has an excellent light-confinement allowing for high solar cell efficiencies. In the case of amorphous silicon single-junction p-i-n solar cells a stabilized record efficiency of 9.47% could independently be confirmed by NREL. This result has been realized on account of the broadband AR-coating applied on the front glass side. QE measurements confirm the exceptional light-trapping of the ZnO leading thereby 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 the 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 is independently confirmed by NREL.

These results suggest that the combination of a high-quality TCO and a single-junction amorphous silicon cell fabrication step allows for a simplification of module manufacturing compared with amorphous multi-junction cells while keeping a high module performance, however, 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 checked with the additional involved costs of the AR.

In the case of micromorph tandem cells, the use of LP-CVD ZnO as front TCO allows for 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 the LP-CVD ZnO technique resulted in an aperture area module efficiency for the micromorph tandems of initially 11% and stabilized 9.8%. By improving both types of cells and by perfecting the series interconnection, a further increase in the stable module efficiency over 10% should be possible.

Micromorph tandem test cells with intermediate ZnO reflector layers between the amorphous top and microcrystalline bottom cell reveal a highly stable performance under prolonged light-exposure. We already obtained a high stable efficiency of 10.7% (without a light-induced decay of the efficiency), 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% should be possible 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 of 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 (≈ 8 or 10%, respectively, for the single-junction and for the tandem case); consequently, this very combination will permit a significant reduction in deposition process times and in material costs, leading to attractively low costs for module manufacturing ($\$1/W_p$ becomes a realistic and attainable value).

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References

[1] S. Faÿ, S. Dubail, U. Kroll, J. Meier, Y. Ziegler, A. Shah, Proceedings of the 16th EU PVSEC (2000) p. 361.
[2] J. Bauer, H. Calwer, P. Marklstorfer, P. Milla, F.W. Schulze, K.-D. Ufert, J. Non-Cryst. Solids 164–166 (1993) 685.
[3] R.G. Gordon, in: C.E. Witt, M. Al-Jassim, J.M. Gee (Eds.), AIP Conference Proceedings, vol. 394. NREL/SNL Photovoltaics Program Review, AIP Press, New York (1997) p. 39.
[4] J. Meier, U. Kroll, S. Dubail, S. Golay. S. Faÿ, J. Dubail, A. Shah, Proceedings of 28th IEEE PVSC (2000) p. 746.
[5] J. Meier, S. Dubail, S. Golay, U. Kroll, S. Faÿ, E. Vallat-Sauvain, L. Feitknecht, J. Dubail, A. Shah, Sol. Energ. Mater. Sol. Cells 74 (2002) 457.
[6] A.V. Shah, J. Meier, L. Feitknecht, E. Vallat-Sauvain, J. Bailat, U. Graf, S. Dubail, C. Droz, Proceedings of 17th EU PVSEC, Munich (2001) p. 2823.
[7] J. Meier, J. Spitznagel, S. Faÿ, C. Bucher, U. Graf, U. Kroll, S. Dubail, A. Shah, Proceedings of 29th IEEE PVSC, New Orleans (2002) p. 1118.
[8] D. Fischer, S. Dubail, J.A. Anna Selvan, N. Pellaton Vaucher, R. Platz, Ch. Hof, U. Kroll, J. Meier, P. Torres, H. Keppner, N. Wyrsch, M. Goetz, A. Shah, K-D. Ufert, Proceedings of 25th IEEE PVSC, Washington, DC (1996) p. 1053.
[9] K. Yamamoto, M. Yoahimi, Y. Tawada, S. Fukuda, T. Sawada, T. Meguro, H. Takata, T. Suezaki, Y. Koi, K. Hayashi, T. Suzuki, M. Ichikawa, A. Nakajima, Sol. Energ. Mater. Sol. Cells 74 (2002) 449.
[10] K. Yamamoto, A. Nakajima, M. Yoshimi, T. Sawada, S. Fukuda, K. Hayashi, T. Suezaki, M. Ichikawa, Y. Koi, M. Goto, H. Takata, Y. Tawada, Proceedings of 29th IEEE PVSC, New Orelans (2002) p. 1110.
[11] K. Yamamoto, A. Nakajima, M. Yoshimi, T. Sawada, S. Fukuda, T. Suezaki, M. Ichikawa, Y. Koi, M. Goto, H. Takata, T. Sasaki, Y. Tawada, Proceedings of Third World Conference on Photovoltaic Energy Conversion, Osaka, in press.
[12] R. Platz, D. Fischer, C. Hof, S. Dubail, J. Meier, U. Kroll, A. Shah, Mat. Res. Soc. Proc. 420 (1996) 51.
[13] R. Platz, D. Fischer, S. Dubail, A. Shah, Proceedings of 14th EC-PVSEC (1997) p. 636.
[14] S. Golay, J. Meier, S. Dubail, S. Faÿ, U. Kroll, A. Shah, Proceedings of 28th IEEE PVSC (2000) p. 1456.
[15] H.J. Gläser, 'Large Area Glass Coatings' (1999) ISBN 3-00-004953-3.
[16] S. Guha, Proceedings of 13th Sunshine Workshop on Thin Film Solar Cells; Technical Digest, Tokyo (2000) p. 25.