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Amorphous solar cells, the micromorph concept and the role of VHF-GD deposition technique

J. Meier [a,*], U. Kroll [a], E. Vallat-Sauvain [b], J. Spitznagel [a], U. Graf [b], A. Shah [b]

[a] *Unaxis SPTec, Puits-Godet 12a, CH-2000 Neuchâtel, Switzerland*
[b] *Institut de Microtechnique, A.L. Breguet 2, CH-2000 Neuchâtel, Switzerland*

Abstract

During the last two decades, the Institute of Microtechnology (IMT) has contributed in two important fields to future thin-film silicon solar cell processing and design:

(1) In 1987, IMT introduced the so-called "very high frequency glow discharge (VHF-GD)" technique, a method that leads to a considerable enhancement in the deposition rate of amorphous and microcrystalline silicon layers. As a direct consequence of reduced plasma impedances at higher plasma excitation frequencies, silane dissociation is enhanced and the maximum energy of ions bombarding the growing surface is reduced. Due to softer ion bombardment on the growing surface, the VHF process also favours the formation of microcrystalline silicon. Based on these beneficial properties of VHF plasmas, for the growth of thin silicon films, plasma excitation frequencies f_{exc} in the range 30–300 MHz, i.e. clearly higher than the standard 13.56 MHz, are indeed scheduled to play an important role in future production equipment.

(2) In 1994, IMT pioneered a novel thin-film solar cell, the microcrystalline silicon solar cell. This new type of thin-film absorber material—a form of crystalline silicon—opens up the way for a new concept, the so-called "*micromorph*" tandem solar cell concept. This term stands for the combination of a *micro*crystalline silicon bottom cell and an *amorphous* silicon top cell. Thanks to the lower band gap and to the stability of microcrystalline silicon solar cells, a better use of the full solar spectrum is possible, leading, thereby, to higher efficiencies than those obtained with solar cells based solely on amorphous silicon.

Both the VHF-GD deposition technique and the "micromorph" tandem solar cell concept are considered to be essential for future thin-film PV modules, as they bear the potential for combining high-efficiency devices with low-cost manufacturing processes.

Keywords: Amorphous silicon; Microcrystalline silicon; Thin film silicon solar cells; Light-trapping; LP-CVD ZnO; VHF-PECVD

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[*] Corresponding author. Tel.: +41 79 705 2377; fax: +41 32 732 5581.
E-mail address: johannes.meier@unaxis.com (J. Meier).

1. Introduction

For large-scale application of photovoltaics (PV) it is imperative to reduce the manufacturing cost of PV modules ($\$/W_p$) by a factor of 2–3, when compared to present prices determined by traditional, wafer-based crystalline silicon PV technology, a module technology that presently dominates the world market. Indeed, in order to turn PV into a competitive energy source in future, such a further substantial cost reduction will be the deciding factor. However, the abandoning of the well-proven concept of "safe" wafer has so far been, without any exceptions, always accompanied by a significant loss in efficiency. The efficiency drops down to less than a half, when compared to record achieved efficiencies of close to 25%, as achieved with monocrystalline silicon wafers (Zhao et al., 1999).

This situation has motivated researchers to intensify the study, since the early '80s to various *thin-film* solar module concepts. In all these thin-film concepts, the semiconductor can be deposited directly on low-cost large-area substrates. Furthermore, the cells do not have to be self-supporting, therefore, large-area substrates can be used; and these substrates may form a part of the encapsulation.

Thin-film solar cells based on compound semiconductors such as CdTe and $Cu(In,Ga)Se_2$ (CIGS), have attracted much attention in the past due to the remarkable work of many groups (Schäffler et al., 1997; Schock and Shah, 1997; Wieting, 2002). On the other hand, amorphous silicon (a-Si:H) technology has now achieved an industrial level (Yang et al., 1998; Tawada and Yamagishi, 2001) and is economically competitive, contributing thereby to a reduction of the module price per W_p. However, a-Si:H has always been associated with low efficiencies, and with further efficiency losses during operation, due to the Staebler–Wronski–Effect (SWE). Still, the low deposition temperature of around 200 °C (as usable for amorphous silicon production) and the application possibility of the monolithic series connection technique for module manufacturing (Carlson et al., 1997; Frammelsberger et al., 1997) were generally considered to be significant advantages for amorphous silicon technology, as they are indeed key features that are needed in order to obtain low manufacturing costs.

The focus of our research group at IMT Neuchâtel has been the development of low-cost concepts for thin-film silicon solar cells. We considered the deposition rate for amorphous and microcrystalline silicon (μc-Si:H) to be a key element for mass production of silicon thin-film solar cells. In 1987, IMT introduced the so-called VHF-GD (very high frequency glow-discharge) technique, allowing for an enhancement, by a factor of 5, of the deposition rate for hydrogenated amorphous silicon (Curtins et al., 1987a,b). In this paper we will review, in Section 2, the main work done in our laboratory and elsewhere, on the VHF deposition technique.

Besides the deposition rate, the solar cell efficiency is an additional important factor to enhance the competitiveness of thin-film solar cells. Ten years ago, in 1994, IMT pioneered microcrystalline silicon solar cells with reasonable conversion efficiencies, showing that this form of thin-film silicon is a promising new PV absorber material (Meier et al., 1994a). Microcrystalline silicon solar cells, used within a tandem cell, as bottom cell offer, furthermore, excellent band gap matching with amorphous silicon top cells; the IMT research group therefore introduced, in 1994, a new thin-film solar cell concept, the so-called "micromorph" solar cell (Meier et al., 1994b). Since then, hydrogenated microcrystalline silicon (μc-Si:H) has been confirmed as a high-quality low-defect semiconductor material with a large application potential and many University groups and Industrial companies have launched research activities in this field.

In thin-film solar cells, light-trapping plays a major key role with respect to reduction of cell thickness and stability of the amorphous silicon solar cells. In all cases, light-trapping is important in reducing the absorber layer thickness and thereby reducing deposition time for the cell, the latter being a major cost factor. In the case of μc-Si:H, light-trapping is specially important, from an economic point of view, as the absorber layer needed here becomes otherwise unrealistically thick. In this context, IMT has developed its own deposition technique for the transparent conductive oxide (TCO) layer, as used in thin-film silicon solar cells: In IMT's case, it is a low-pressure chemical vapor deposition (LP-CVD) technique for ZnO layers: a method that allows for the high-rate deposition of as-grown rough ZnO layers with excellent optoelectronic properties and improved light-trapping, as needed for all silicon thin-film solar cells.

2. VHF-GD deposition technique

It has been shown by several groups (Curtins et al., 1987a,b; Zedlitz et al., 1992; Howling et al., 1992; Chatham and Bhat, 1989; Oda et al., 1988, 1990) that an increase in plasma excitation frequency from the standard frequency of 13.56 MHz to values in the VHF range, e.g. between 70 and 130 MHz, permits an increase in deposition rate by a factor of 4–10, both for a-Si:H as well as for μc-Si:H layers. Curves of deposition rate vs. excitation frequency (Fig. 1) possess, in general, a maximum at a certain "optimal" frequency and show, thereafter, a decrease of deposition rate for yet higher frequencies: this decrease can be attributed to engineering aspects like reactor design (i.e. to an increase in electrical losses as the excitation frequency is increased). On the other hand, the general trend of an increase in deposition rate

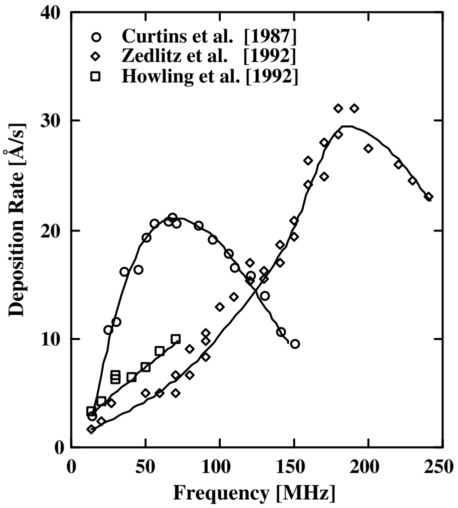


Fig. 1. Deposition rate for hydrogenated amorphous silicon (a-Si:H) layers in a silane plasma (without hydrogen dilution), vs. plasma excitation frequency, as obtained in different reactors and by independent research groups. Data taken from Curtins et al. (1987a,b), Zedlitz et al. (1992) and Howling et al. (1992).

with increasing excitation frequency can be attributed to fundamental physical changes in the capacitively-coupled glow discharge plasma: As the excitation frequency is increased, the sheath thickness decreases and the plasma impedance significantly changes.

Fig. 2 presents the results of plasma impedance measurements on a hydrogen plasma, observed as the frequency is increased from 40 MHz to 70 MHz (Kroll et al., 1994). The resistive component (Re Zplasma) and the absolute value of the reactive component (Im Zplasma) decrease with increasing excitation frequency: With increasing excitation frequency the plasma takes on a more resistive character and the total impedance decreases. Based on a simple equivalent circuit model (Kroll et al., 1994) for the discharge, the plasma reactance can be directly linked with the sheath capacitance and, hence, to the thickness of the two sheaths present in the discharge. Higher frequencies lead to a significant increase in the sheath capacitance and, thus, to a pronounced decrease in sheath thickness (see Fig. 3): the latter decreases from 2.2 mm to 1.4 mm, as the plasma excitation frequency is increased from 40 MHz to 70 MHz (Kroll et al., 1994).

Fig. 4 shows the measured values of the RF-voltage at the powered RF electrode during the plasma impedance measurement (Fig. 2). The reduction in RF-voltage at higher frequencies reflects the trend also observed in pure silane discharges (Howling et al., 1992) and is a direct outcome of the reduced reactive plasma impedance and of the thinner sheaths (Kroll, 1995).

Both these observations are in agreement with experimental and theoretical studies by other groups (Beneking, 1990; Beneking et al., 1992; Surendra and Graves, 1991) and can be considered to constitute a general physical effect prevalent in capacitively-coupled VHF-plasmas.

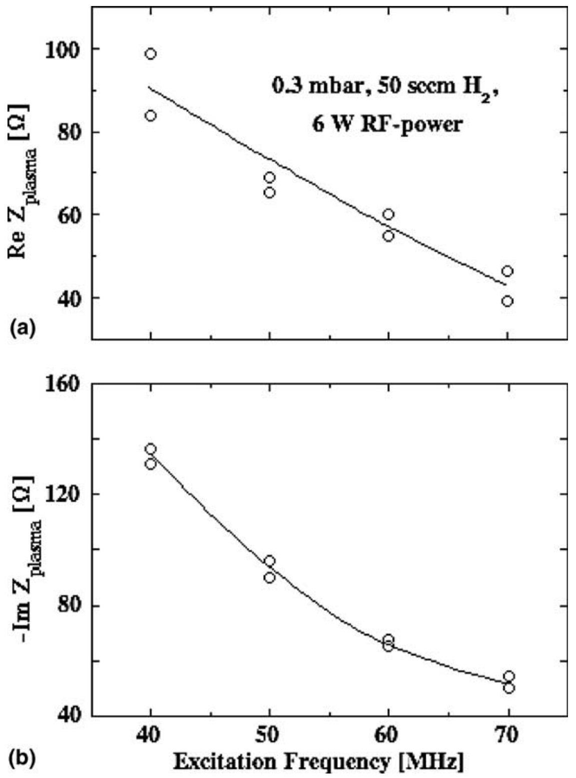


Fig. 2. Real part (a) and negative imaginary part (b) of the plasma impedance as a function of plasma excitation frequency, for a capacitively-coupled glow discharge plasma of pure silane. Data taken from Kroll et al. (1994).

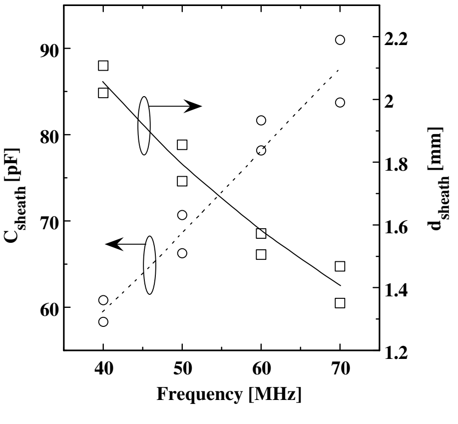


Fig. 3. Sheath-capacitance and corresponding calculated sheath-thickness of a hydrogen plasma vs. the plasma excitation frequency, for the plasma reactor of Fig. 2. Data taken from Kroll et al. (1994).

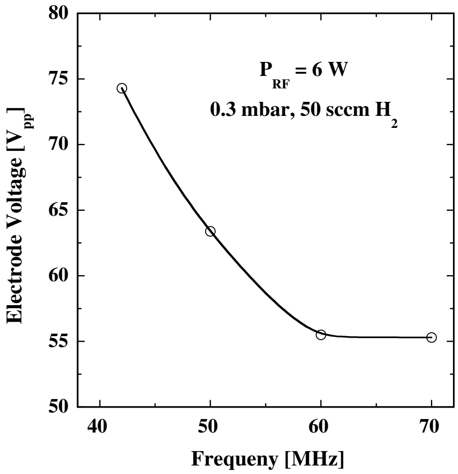


Fig. 4. RF-voltages measured at the powered electrode as a function of plasma excitation frequency, for the plasma reactor of Fig. 2. Data taken from Kroll (1995).

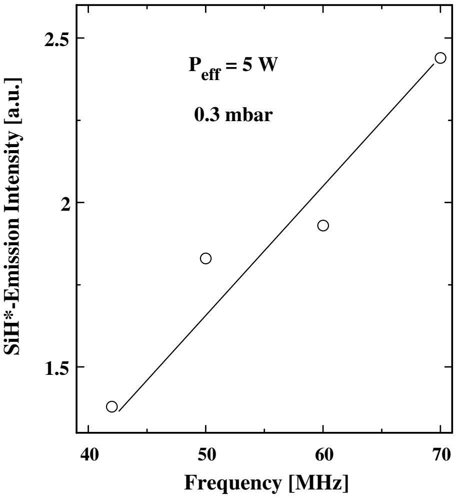


Fig. 5. Global optical SiH* plasma emission intensity at constant plasma power vs. the plasma excitation frequency, for a capacitively-coupled glow discharge plasma of pure silane. Data taken from Howling et al. (1992).

There are two consequences of the thinner plasma sheaths and the lower RF-voltage on the powered electrode: first, the sheath potential and, hence, the ion bombardment on the growing layer is reduced; second, the RF-power is more efficiently coupled-in into the bulk plasma (rather than into the sheath, as is the case at lower plasma excitation frequencies). Due to the second effect, higher electron densities and better SiH_4 dissociation in the bulk plasma, as well as increased radical and ion flux onto the growing surface, can be achieved. An end result of all this is a net increase in the deposition rate, without any deterioration in layer quality.

The above considerations are, indeed, based on the following additional experimental observations: Strong experimental indications (Howling et al., 1992) for a higher dissociation of the silane in the bulk plasma were obtained from a measured increase of the optical emission of the SiH*-line at higher frequencies while keeping the effective plasma power constant (see Fig. 5). It has to be noted that in pure silane plasmas, the optical emission intensities of the SiH*-line represent a rough measure for the electron density (Perrin and Schmitt, 1982; Perrin and Aarts, 1983) prevalent in the plasma.

Heintze et al. (Heintze et al., 1993; Heintze and Zedlitz, 1996) have measured an enhanced ion flux on the growth surface at higher frequencies (see Fig. 6) which is related to the changes in both the bulk plasma and in the sheath. They suggested that the enhanced ion flow to the growing surface could well be the growth-rate controlling mechanism in the deposition of the a-Si:H material, because (as they argued) it would result in an increased surface reactivity of the film precursors.

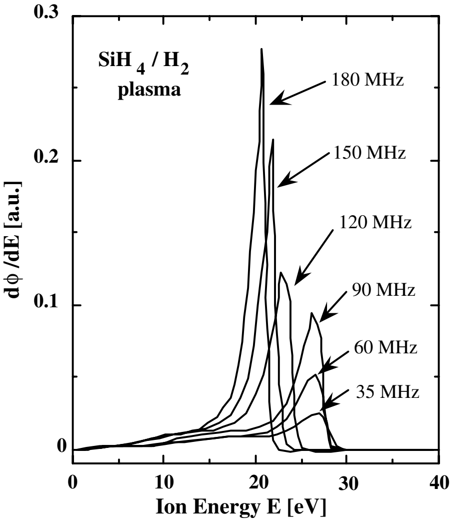


Fig. 6. Energy distribution of ions impinging on the substrate in a silane/hydrogen plasma for different plasma excitation frequencies, for a capacitively-coupled glow discharge plasma of pure silane. Data taken from Heintze and Zedlitz (1996).

The observed reduced peak ion energy at higher frequencies as found in the direct flux measurements (Fig. 6) is a direct consequence of the reduction in RF voltage and, thus, of the reduced plasma sheath potential. The higher ion flux and the lower energy of the ion bombardment lead to a “softer” but “intensified” ion bombardment and might be a reason why VHF-plasmas favour microcrystalline growth.

3. Use of LP-CVD ZnO for efficient light-trapping

The possibility to use rough transparent conductive oxide contact layers in order to obtain efficient light-trapping is fundamental in increasing the efficiency of thin-film silicon solar cells. Thus, high transparency, high electrical conductivity, and high light-scattering ability are the necessary material parameters for a high-quality TCO. With the help of an appropriate TCO layer the effective optical absorption can be significantly increased (both for amorphous, as well as for microcrystalline silicon) allowing, thereby, for a reduction of the absorber thickness. In the case of amorphous silicon, this advantage leads to improved cell stability, and in the case of microcrystalline silicon, to a significant reduction in deposition time and production costs.

The key role of the TCO layers for thin-film silicon 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 (Faÿ et al., 2000; Bauer et al., 1993; Gordon, 1997). This particular TCO has notable advantages for thin-film solar cells in general: ZnO itself is an abundant and low-cost material. Our specific 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, our LP-CVD process leads directly to an as-grown high texturing of the ZnO films, as shown in Fig. 7. Furthermore, the low process temperatures of around 200 °C involved here are entirely compatible with low-cost substrates (inexpensive glass, polymers, aluminium, stainless steel etc.), and furthermore, correspond to the low process temperatures employed in the PECVD (plasma enhanced chemical vapour deposition) production methods, as used for the deposition of the amorphous and microcrystalline silicon layers themselves.

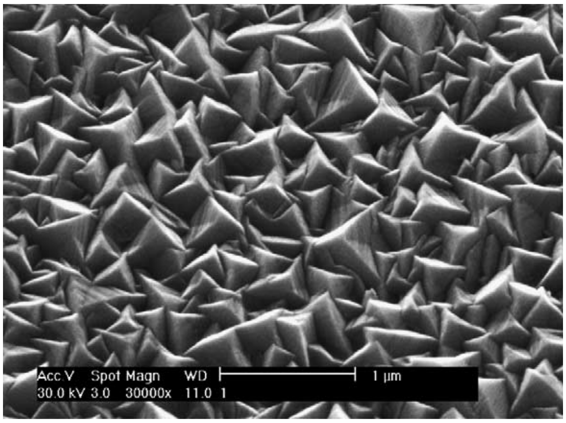


Fig. 7. Surface texture of a typical as-grown LP-CVD ZnO layer as incorporated in IMT's p–i–n solar cells.

Recently we have compared our "in-house" ZnO layers with the best commercially available SnO_2 (Asahi U-type) TCO layers; this was done within p–i–n configurated solar cells, both within amorphous single-junction and micromorph tandem devices (Meier et al., 2000, 2002a,b; Shah et al., 2001). For both amorphous single-junction cells and micromorph tandems, LPCVD ZnO shows superior performance, resulting in higher current densities and improved quantum efficiencies in the red and near-infrared spectral regions of the solar spectrum, when compared to U-type SnO_2 from Asahi Glass Corp. This enhancement is due to the better light-trapping capability of our "in-house" ZnO layers, resulting in a higher short-circuit-current (J_{sc}) of the solar cell, while fill factor (FF) and open circuit voltage (V_{oc}) remain identical for both SnO_2 and ZnO. Thus, LPCVD ZnO allows one to reduce the absorber thickness while preserving a high efficiency potential.

4. PECVD of thin-film silicon solar cells

4.1. General experimental procedure

For the preparation of the ZnO coated substrates, AF45 Schott glass with a thickness of 0.7 mm was used. The ZnO layers applied have a thickness of about 2.2 µm and a sheet resistance of 6–8 Ω/sq. The a-Si:H p–i–n and micromorph a-Si:H/µc-Si:H tandem solar cells were fabricated by VHF-PECVD in a laboratory reactor with substrate area of $8 \times 8\,cm^2$. The deposition rates for both the amorphous and the microcrystalline intrinsic layers were approximately 0.5 nm/s. For details on a-Si:H p–i–n cell fabrication, by VHF-GD, as developed by IMT, we refer to our earlier publications (Platz et al., 1996, 1997 and references therein).

An important requirement of a TCO-coated glass is the compatibility with the plasma processes used for depositing thin-film silicon cells on it (this is a problem e.g. with SnO_2 which is reduced by a hydrogen-rich plasma). Furthermore, the TCO used should also allow for subsequent laser-scribing, as generally required for large-area module manufacturing. In fact, short circuits and other electrical defects resulting from a faulty series interconnection of the segments is often the cause of a bad performance (low FF) of the modules (Golay et al., 2000). In our case, laser-structuration of the three scribe patterns was investigated in combination with LP-CVD ZnO, as front TCO, for mini-modules, for both the very thin amorphous single-junction and the thicker micromorph tandem cells.

The solar cells and modules were characterised using an AM1.5 global two light-source sun simulator (Wacom WXS-140 S-10). In addition, test cells were analysed by quantum efficiency (QE) measurements. The light-soaking of cells and modules was performed under illumination with a spectrum close to AM1.5 (1 sun intensity) and at 50 °C device temperature, as well as at open circuit conditions. After the light-soaking experiments amorphous silicon single-junction p–i–n cells and modules were sent to NREL (National Renewable Energy Laboratory, USA) for independent AM1.5 I-V and QE characterisation.

4.2. 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 single-junction p–i–n cells when applying LP-CVD ZnO as front TCO (Meier et al., 2000). Since at IMT we have all fabrication steps for cell and module fabrication technology in our lab, it was also easy for us to further improve the coupling of the incoming light into our modules by applying an antireflective (AR) coating. In this experiment, 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 (Gläser, 2000). They consist of a multi-layer design: glass/A/B/A/B (A = TiO_2 or Nb_2O_5, B = SiO_2).

Fig. 8 reveals the impact of the AR-coating on the reflectivity of amorphous p–i–n cells in comparison with cells on non-coated substrates of LP-CVD ZnO and SnO_2 (U-type, from Asahi Glass). While ZnO already results in a reduced reflectance compared to 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 spectral range of the sun, where absorption by the a-Si:H p–i–n cell is high. The remaining absorption loss of 2.5–2.6% is mainly due to the reflection at the glass/ZnO interface as a spectral analysis of the AR-coated glass substrate by itself reveals.

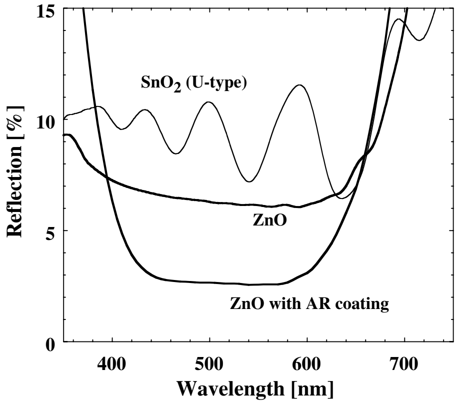
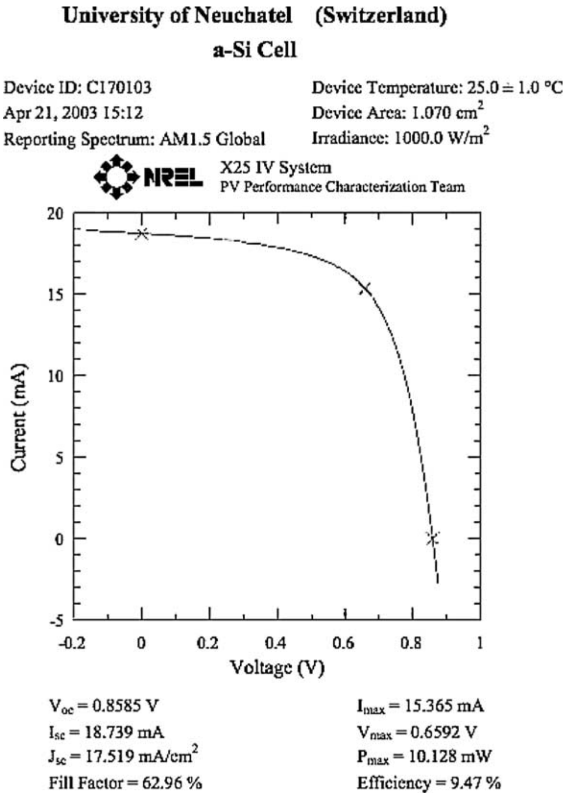


Fig. 8. Reflection behavior as measured from the glass side of amorphous p–i–n cells deposited on SnO_2 (Asahi U), on LP-CVD ZnO and on LP-CVD ZnO with an antireflective (AR) coating. The AR coating reduces the reflectance by about 4%.

Amorphous p–i–n cells prepared on AR-coated ZnO glass substrates were sent after light-soaking to NREL for independent characterization. Fig. 9 independently confirms the *I–V* characteristics for AM1.5 global illumination 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 possesses a rather high 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 by NREL) before light-soaking.

The spectral analysis of the photocurrent in Fig. 10 (measurement done by NREL) of the 9.47% cell shows a remarkably high quantum efficiency even in the degraded state. The QE-values reach a level of 94% in the important part of the sun spectrum, where the light absorption by the cell should be high. This indicates a high transparency, and a high light-trapping capacity for LP-CVD ZnO as front TCO, resulting, in high values of photocurrent density. The efficiency of 9.47% is to our knowledge the highest independently-confirmed effi-



University of Neuchatel (Switzerland)
a-Si Cell

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

X25 IV System
PV Performance Characterization Team

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

Fig. 9. NREL certified *I–V* characteristics 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, reflection data of which is shown in Fig. 8.

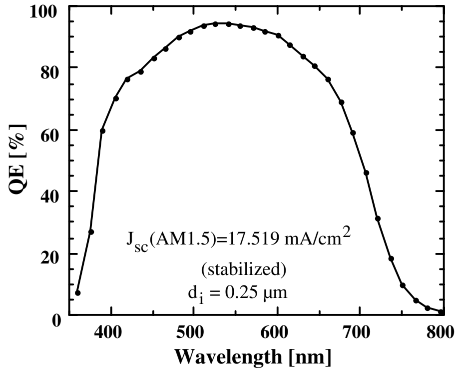


Fig. 10. NREL-certified quantum efficiency of the light-soaked 9.47% efficiency a-Si:H p–i–n solar cell of Fig. 9.

ciency value for stabilized single-junction a-Si:H devices (compare also with: Yang et al., 1998).

4.3. Micromorph silicon tandem cells

Micromorph (a-Si:H/µc-Si:H pin/pin) tandem cells have been fabricated on LP-CVD ZnO used 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 range up to a maximal thickness of 0.25 µm. Fig. 11 shows for the tandem cell an initial efficiency of over 12% combined with a high open circuit voltage of 1.4 V. After light-soaking, a stabilized efficiency of 10.8% could be obtained.

4.4. Intermediate reflector in micromorph tandem cells

Within the micromorph tandem, it is the amorphous top cell that provides roughly 2/3 of the total power, but this top cell is at the same time the current-limiting cell, because it has to be kept very thin (in order to avoid excessive light-induced degradation) and it does not directly benefit from reflection and additional light-scattering by the back reflector. Because of this, IMT introduced in 1996 the concept of a ZnO layer acting as an intermediate reflector between the amorphous top and microcrystalline bottom cell (Fischer et al., 1996). This concept permits an increase of the a-Si:H top cell photocurrent due to reflection by the interlayer, based on the difference in the refraction index of the two silicon p–i–n cells and the interlayer. Thanks to the high infrared photocurrent potential and the stability of the microcrystalline bottom cell a matching of the gained a-Si:H top cell current can principally be achieved by adapting the µc-Si:H bottom cell to larger thicknesses. 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. Applying this intermediate reflector layer concept in a-Si:H/c-Si:H tandems, Yamamoto et al. (2002a,b, 2003) have recently demonstrated a notably high initial efficiency of 14.7% for a test cell device.

The impact of an intermediate TCO layer on the QE of top and bottom cells, within micromorph tandems, is illustrated in Fig. 12. Top a-Si:H cells of 0.18 µm thickness, with an interlayer can easily achieve similar photocurrent densities as top cells of 0.25 µm thickness without internal TCO layers. In contrast to recent results presented by Yamamoto et al. (2002a,b, 2003), we always observe a loss in the photocurrent density of the bottom cell with our own intermediate reflectors.

Micromorph tandems fabricated by us with intermediate reflectors can demonstrate a surprisingly stable performance. As Table 1 shows, there is no significant change in *I–V* characteristics of this particular cell (with an intermediate reflector) after a period of over 1300 h of

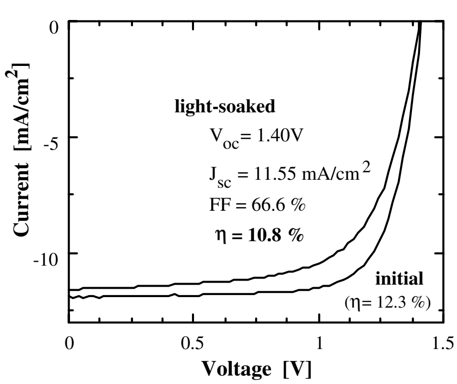


Fig. 11. AM1.5 *I–V* characteristics of a micromorph tandem test cell deposited on glass/LP-CVD ZnO in the initial and stabilized state (after 1000 h of light-exposure at 1 sun and 50 °C). The µc-Si:H bottom cell has a thickness of 2 µm.

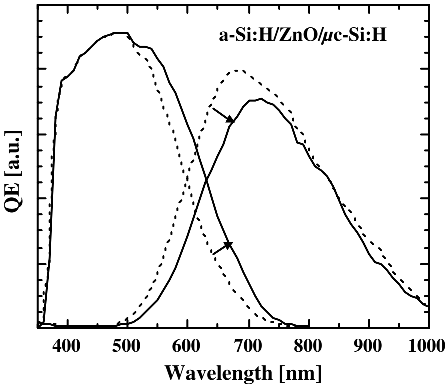


Fig. 12. Effect of the intermediate TCO layer on the quantum efficiency of the a-Si:H top and µc-Si:H bottom cells. The dashed lines show the tandem without the interlayer, the solid lines represent the one with the incorporated intermediate TCO layer.

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.

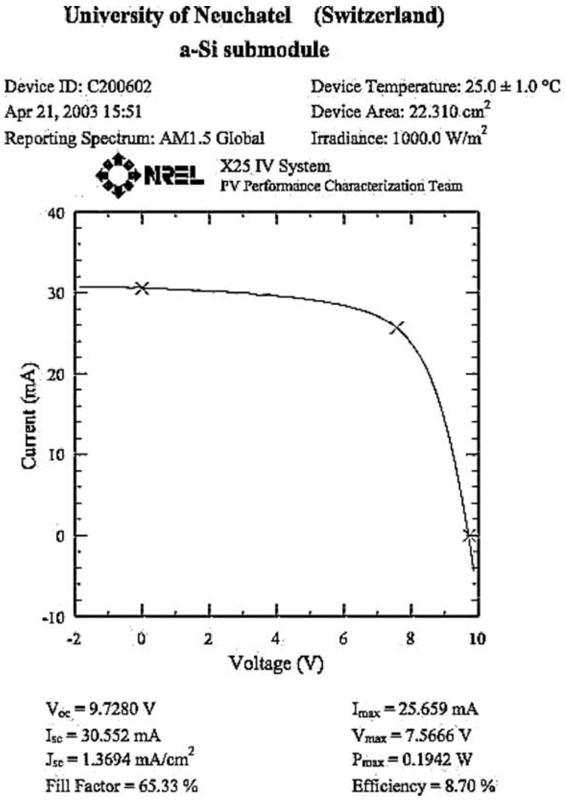
light-soaking. Indeed as the micromorph tandem cell in Table 1 is bottom-limited, and as the a-Si:H top cell is in this case very thin (<0.2 μm), the fill factor is principally given by the stable μc-Si:H bottom cell and is, therefore, less influenced by small light-induced alterations in the a-Si:H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

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 foremost 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, so as to be cost-effective. With respect to large-area module mass production the additional process steps, the longer fabrication time of the thicker μc-Si:H bottom cell and the task of the series interconnection by laser-scribing have to be carefully investigated and well balanced with the overall gain in efficiency.

4.5. Amorphous silicon modules

Submodules based on LP-CVD ZnO covered glass substrates were fabricated for amorphous single-junction p–i–n devices applying the integrated monolithic series connection. Fig. 13 gives the AM1.5 *I–V* characteristics of an 11-segmented module with 22.31 cm^2 aperture area in the stabilized state (after 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. 13 reveals that a high quality front TCO (such as IMT's LP-CVD ZnO) has the potential to achieve reasonably high stabilized efficiencies even for a very simple device, i.e. for the a-Si:H p–i–n *single-junction* cell. This certainly has economical advantages. Indeed, the manufacturing of such single-junction cells is clearly more "robust", when compared to sophisticated multi-junction solar cells based on amorphous silicon and silicon–germanium alloys with their very thin partial cells, their many interfaces and their tuned absorber thicknesses. Furthermore, the use of germane as a somewhat problematic source gas (cost!) is completely avoided. In terms of mass production, this simplification should therefore contribute to significantly reducing the manufacturing costs for the modules (\$/W_{p}).



University of Neuchatel (Switzerland)
a-Si submodule

Device ID: C200602
Apr 21, 2003 15:51
Reporting Spectrum: AM1.5 Global
Device Temperature: 25.0 ± 1.0 °C
Device Area: 22.310 cm^2
Irradiance: 1000.0 W/m^2

V_{oc} = 9.7280 V
I_{sc} = 30.552 mA
J_{sc} = 1.3694 mA/cm^2
Fill Factor = 65.33 %
I_{max} = 25.659 mA
V_{max} = 7.5666 V
P_{max} = 0.1942 W
Efficiency = 8.70 %

Fig. 13. AM1.5 global *I–V* characteristics 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 @ 50 °C). The i-layer has a thickness of 0.25 μm.

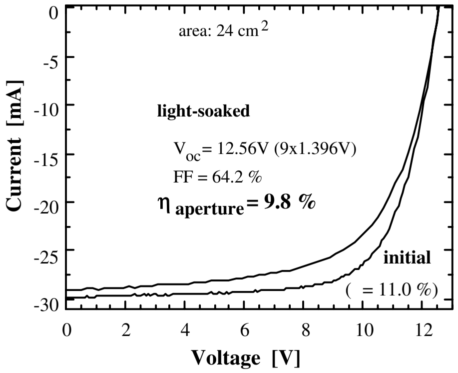


Fig. 14. AM1.5 global *I–V* characteristics of a micromorph tandem cell module fabricated on LP-CVD ZnO-coated glass in the initial and light-soaked state (1000 h under 1 sun and 50 °C). The μc-Si:H bottom cell has a thickness of 2 μm.

4.6. 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 given in Fig. 14.

The module has in the initial state an aperture efficiency of 11% that confirms the satisfactory quality of the series interconnection developed by us. 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.

5. Summary and conclusions

Research developments made at the IMT Neuchâtel group in recent years can be considered to be of major importance for the next generation of thin-film silicon solar cells and modules. The introduction of the VHF-GD deposition technique by IMT in 1987 has since turned out to be a powerful option for reducing deposition time and, hence, costs for all types of future thin-film silicon PV modules. The increased deposition rates observed in VHF plasmas can be attributed to changes in the plasma leading to an enhanced dissociation of the silane in the plasma. Furthermore, at higher frequencies reduced energies of the ions impinging on the growing surface are observed which lead to a "softer" plasma and, thus, to reduced defect creation in crystallites. These findings might explain why VHF-plasmas favour the growth of microcrystalline silicon.

The introduction of hydrogenated microcrystalline silicon as crystalline thin-film PV absorber material by IMT in 1994 has opened up new strategies for high-efficiency thin-film solar cells: namely the use of microcrystalline silicon as a bottom cell, within a tandem configuration, in combination with an amorphous silicon top cell. The gaps of microcrystalline silicon and amorphous silicon form together, in fact, a theoretically ideal pair for a tandem cell (Shah et al., 2004). This "micromorph" concept introduced by IMT in 1994, consisting of a microcrystalline silicon bottom cell and an amorphous silicon top cell, is considered today to be one of the most promising thin-film solar cell concepts and has been taken up for further research by many groups worldwide. First industrially processed a-Si:H/μc-Si:H large-area modules are already available on the Japanese market.

IMT's recent research on light-trapping suggests that the application of a high-quality ZnO will indeed allow one to further improve the conversion efficiency of thin-film silicon solar cells in the p–i–n configuration and, at the same time, reduce the absorber thickness to economically feasible values.

Low-cost, high-quality TCO layers and economical mass-production fabrication processes (such as LP-CVD ZnO and VHF-PECVD) are, thus, becoming the necessary tools for the next generation of thin-film silicon modules. They are essential for the reduction of the high module manufacturing costs so far associated with PV.

Using LP-CVD ZnO amorphous single-junction and "micromorph" tandem solar cells 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). This very combination will also allow for a significant reduction in deposition process times and in material costs, leading to attractively low costs for module manufacturing.

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