MICROCRYSTALLINE AND MICROMORPH THIN-FILM SILICON SOLAR CELLS

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ABSTRACT: This paper deals with 4 separate issues: (1) Open circuit voltage (V_{OC}) of microcrystalline silicon (µc-Si:H): The V_{OC}-value of the single-junction µc-Si:H bottom cell has a direct impact on the efficiency of the "micromorph" (µc-Si:H/a-Si:H) tandem cell. It is shown here that open circuit voltage values of 530 mV can be achieved for µc-Si:H, leading thereby to single-junction cell efficiencies of 8.5 %. (2) The laser-scribing technique commonly used in amorphous silicon technology has been successfully applied on thick µc-Si:H cells. (3) A combination of the hot-wire and VHF-GD deposition techniques allows one to deposit µc-Si:H films with low subbandgap absorption (as measured by PDS) at remarkably high deposition rates of up to 26 Å/s. (4) The behaviour of different solar cells was characterised by the illuminated I-V characteristics in function of cell temperature. Microcrystalline cells with V_{OC}-values higher than 500 mV and "micromorph" tandems possess in general a lower value of the temperature coefficient of the fill factor and thus of the efficiency, when compared to crystalline silicon. Experimental evidence is provided for this.

Keywords: Microcrystalline Si - 1: Tandem Solar Cell - 2: VHF-GD - 3

1. INTRODUCTION

Intrinsic hydrogenated microcrystalline silicon (µc-Si:H) has been shown to be a very promising new photovoltaic material [1-7] for thin-film (< 5 µm) solar cells. Thanks to the Very High Frequency Glow Discharge (VHF GD) technique [8], substrate temperatures as low as 200 •C can be used for deposition. Microcrystalline silicon single-junction p-i-n conversion efficiencies of 7.7 % were obtained already in 1996 [3], however, with a relatively low open circuit voltage (V_{OC}) of around 450 mV. The combination of both amorphous and microcrystalline material leads to a "true" silicon-based tandem concept (no alloys involved, two distinct bandgaps), which has been called the "micromorph" concept. Recently, our group has reported stabilised micromorph efficiencies for a 10.7 % cell (independently confirmed [4]) and, for another tandem with 12 % (not yet confirmed; measurements based on outdoor conditions [5]). In these tandems µc-Si:H bottom cells with a V_{OC} of approximatively 450 mV were incorporated. Obviously, higher efficiencies for micromorph tandem cells could be obtained, if the V_{OC} of the µc-Si:H bottom cells is increased. In the first part of this paper, new results on µc-Si:H single cells, with increased values of V_{OC}, are presented.

Thin-film solar cell concepts are, in general, expected to reduce manufacturing costs for solar cells basically due to two factors: i) reduced material requirements; ii) application of monolithic series connection for module manufacturing. The latter point stresses the necessity of laser-scribing. This technique is well-established for a-Si:H, CIS and CdTe; however, it has to be carefully developed for any new alternative thin-film concepts. In order to check this for µc-Si:H, first experiments with laser-scribing were performed on thick µc-Si:H cells (3-4 µm).

Another important issue for microcrystalline single-junction and micromorph tandem cells is the deposition rate. Hereby, the deposition time of the intrinsic microcrystalline absorber layer is crucial with respect to module manufacturing at industrial production levels. Since it is known that the hot-wire deposition technique leads to very high deposition rates for silicon films, we performed experiments using a combination of the hot-wire and of the VHF-GD technique for microcrystalline silicon deposition; first results are presented here.

Under real working conditions, i.e. outdoor conditions, an important aspect of any solar cell is its temperature performance. The value of installed W_{peak}, e.g. on a roof, usually does not take temperature effects into account; the latter have, however, a direct impact on the yearly energy yield of a given installation. It has been reported that a-Si:H has the best temperature performance in comparison with c-Si and CIS [9]. In the fourth part of this paper we focus our attention on the temperature behaviour of µc-Si:H single-junction and micromorph tandem cells.

2. EXPERIMENTAL

The deposition of microcrystalline p-i-n solar cells has been described in previous work [1-7]. A careful reoptimisation of the p-doped layers [10] and a better control of impurity contaminations in the i-layer were carried out leading to a further improvement in cell performance. The silane gas purifier technique introduced by our group [3,6,11] was used for the deposition of all µc-Si:H i-layers. The cells were characterised under AM1.5 conditions at 100 mW/cm^2 by a two-source solar simulator and spectral response. For the temperature-dependent measurements, a Pt100 sensor was glued onto the back side of the cells. The cells were kept in an isothermal environment by a "heating box" equipped with a glass window in order to illuminate the devices. The temperature variation during an I-V scan was less than 1 K for all measurements. The temperature was varied from 10 •C to 90 •C. The comparison between the different kinds of solar cells investigated was carried out looking at the relative temperature coefficient (TC) which is defined in the following expression:

$$TC(\eta) = \frac{\Delta\eta}{\Delta T \cdot \eta(25°C)} \qquad (1)$$

The structuring of the microcrystalline cells was performed by a conventional NdYAG laser equipped with a frequency doubler. The quality of the scribe w.r.t. electrical losses was monitored by Light Beam Induced Current (LBIC) mapping.

In order to increase the deposition rate of microcrystalline silicon a combination of the hot-wire (HW) and the VHF-GD technique was investigated. The temperature of the glass substrate (Schott AF45 sodium-free) was kept at around 350 •C. The quality of the films was characterised by Photothermal Deflection Spectroscopy (PDS). The description of details of the experimental procedures used for the combined HW/VHF-GD deposition process would exceed the framework of this paper; we limit ourselves to simply announce the possibility of obtaining high-rate deposition of low defect density µc-Si:H.

3. RESULTS AND DISCUSSION

3.1 Microcrystalline silicon solar cells with V_{OC} > 500 mV

The efficiency of micromorph tandem cells is directly linked to the open circuit voltages of the µc-Si:H bottom cell. Up to now, V_{OC}-values higher than 450 mV resulted (in the context of low-temperature VHF-GD at about 200 •C) in moderate FF not higher than 60 %. Therefore, special efforts were invested exclusively for the preparation of µc-Si:H single-junction cells, with the goal to overcome the V_{oc}-FF problem. The results of these new µc-Si:H cells are given in Tab. I, where it can be clearly seen that V_{OC}-values over 500 mV combined with good fill factors are obtainable for µc-Si:H cells. The so far best cell showed a V_{OC}-value as high as 531 mV and a fill factor close to 70 %, which leads to a AM1.5 cell efficiency of 8.5 %. Note, that an even further improvement of the open circuit voltage close to 600 mV can be obtained (Tab. I); however, the simultaneous achievement of high fill factors, remains yet to be accomplished.

These new high-V_{OC} bottom cells will have, of course, a direct impact on the efficiency of micromorph tandem cells. The prospects for future micromorph cell efficiencies in function of the open circuit voltage of the bottom cell can be seen in Fig. 1; the lines indicate the projected efficiencies for single-junction µc-Si:H and for tandem cells.

The new experimental results on µc-Si:H single cells from Tab. I (filled circles) indicate the efficiency potential for the next generation of micromorph cells: We can assume, thus, that stable efficiencies of 13 % should be achievable by implementation of our present bottom cells within the tandem structure. This has yet to be carried out in the next step of our work.

3.2 Laser-scribing

Without any doubt, the laser-scribing technique is one of the key factors in reducing production costs for all thin-film solar cell concepts. Keeping this fact in mind, we have to now check carefully: (i) the compatibility of laser-scribing with relatively thick silicon layers and ii) the scribing technique of crystalline silicon in form of µc-Si:H based devices (single junctions and micromorph tandems). It is thus mandatory to prove that such devices can be laser-scribed without significant losses in the cell performance.

The SEM micrograph represented in Fig. 2 shows that patterning of a 3.5 µm thick cell is possible, i.e. requirement (i) is fulfilled. In Fig. 2 the individual "shots" of the laser pulses can be seen.

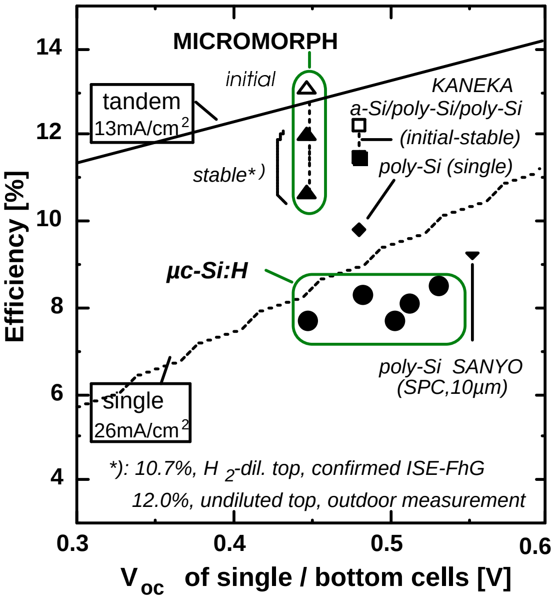

Figure 1: Projected efficiencies of micromorph tandem cells in function of the V_{OC} of the µc-Si:H bottom cell, assuming a total current of 26 mA/cm^2, a fill factor of 73 % and a V_{OC} of 900 mV for the a-Si:H top cell (lines). Symbols represent experimentally obtained data (SANYO in ref. [12], KANEKA in ref. [13]).

Table I: Recent new µc-Si:H single p-i-n solar cells.

η [%]	7.7	8.3	7.7	8.1	**8.5**	3.2	4.4
J_{SC} [mA/cm^2]	25.3	25.2	21.5	23.2	22.9	18.4	17.9
FF [%]	67.9	68.2	71.1	68	69.8	30.5	41.8
V_{oc} [mV]	**448**	**483**	**503**	**512**	**531**	**568**	**592**

Figure 2: SEM photograph of a laser-scribed micro-crystalline silicon p-i-n solar cell deposited onto TCO-coated glass.

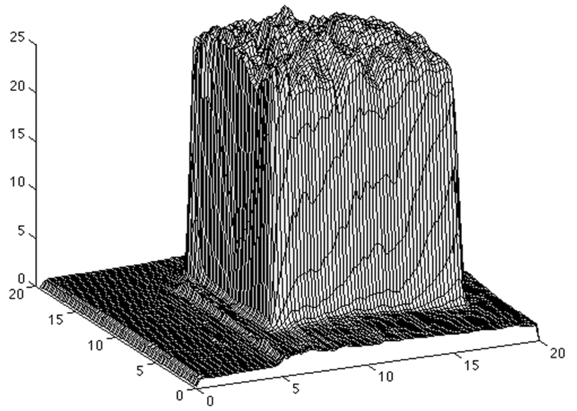

Figure 3: LBIC mapping of a 1x1 cm^2 µc-Si:H p-i-n cell patterned by laser-scribing.

Patterning alone is merely the first step for the establishment of the laser-scribing technique; the conservation of the electrical properties of the solar cell during laser-scribing must be guaranteed. In order to check this, LBIC mapping combined with I-V characteristics was performed. The LBIC map of a square-shaped laser scribed µc-Si:H cell is represented in Fig. 3. Note the very steep decrease of the photocurrent in the vicinity of the scribed lines: this indicates that there is no deterioration of the electrical properties at the border of the cell. Globally, we could not detect a reduction of the active area cell efficiency. Thus, one may conclude that conventional laser-scribing can be applied to thin-film crystalline silicon. The full set of such experiments were not yet carried out on micromorph cells.

3.3 Results on high rate deposition of µc-Si:H

It is well-known from previous work [14, 15] that the hot-wire (HW) technique (also called "catalytic CVD") allows one to grow silicon films at significantly higher deposition rates as compared to glow-discharge. However, polycrystalline silicon deposited by this method generally shows higher subbandgap absorption [16] when compared to similar material deposited by VHF-GD. Our idea was to **combine** both these processes. Results for films deposited with such a **combination** of **HW and VHF-GD** are shown in Fig. 4, where the following striking observations can be made:

i) a remarkably high deposition rate as high as 26 Å/s could be achieved without powder formation for microcrystalline silicon.

ii) we observe (by PDS) a similarly low subgap absorption value for these films (at 0.8 eV) when compared to films deposited by VHF-GD. This indicates that this material should basically be suitable for solar cells.

iii) compared to VHF-GD films, however, the combined VHF-GD/HW material shows lower apparent absorption at the bandedge (1 to 1.8 eV). This can probably be explained by a lack of microstructural features that enhance light-scattering at the surface, and by that, the apparent absorption [17, 18].

The encouraging material by VHF-GD/HW should now be transferred in further steps into a full p-i-n structure: Only in this way can one prove that such high-rate material is really useful for solar cells.

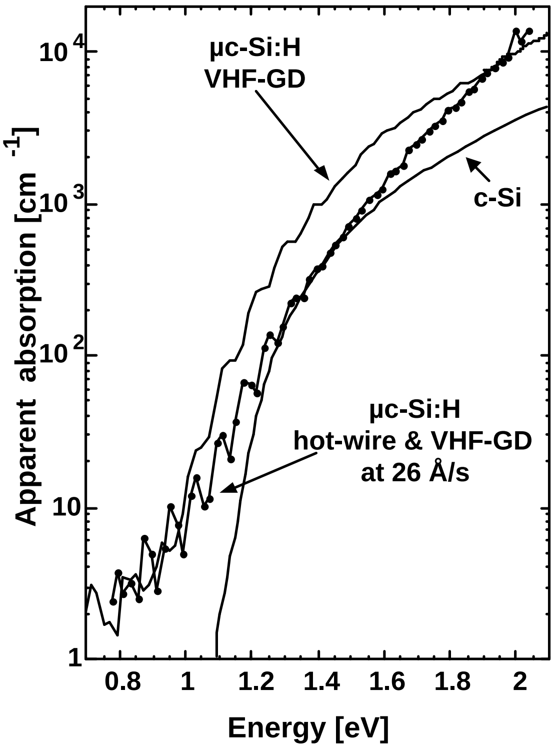

Figure 4: Apparent optical absorption of a high-rate µc-Si:H layer (26 Å/s) deposited by the combined hot-wire (HW) and VHF-GD technique in comparison with results obtained for VHF-GD µc-Si:H layers [1] and with the optical absorption of monocrystalline silicon (c-Si).

3.4 Temperature-dependent illuminated I-V measurements

A comprehensive set of solar cells (six µc-Si:H, three micromorph tandems, two crystalline silicon cells and one a-Si:H) was measured in function of the device temperature. The results are briefly summarised in Tab. II.

a) Single-junction cells

First of all, the temperature dependency of crystalline and amorphous silicon was investigated. Fig. 5 demonstrates the well-known fact that the decrease of efficiency at higher temperatures of amorphous silicon solar cells is much lower than that of crystalline (wafer-based) silicon cells [9].

How do the µc-Si:H single-junction and micromorph tandem cells behave at higher temperatures? In order to answer this question, such cells were subjected to the same temperature procedure as for the ones shown in Fig. 5: The results for single-junction µc-Si:H cells are given in Fig. 6 and Tab. II. The most striking difference between the c-Si and the µc-Si:H cells consists in a significantly reduced fill factor loss for µc-Si:H cells at higher temperatures; whereas the V_{OC}- and the J_{SC}-dependencies are comparable to those of (wafer-based) crystalline silicon (c-Si). The conservation of the fill factor of µc-Si:H cells at higher temperatures becomes even more pronounced for cells where V_{OC}-values at 25 °C exceed 500 mV. Cells with lower V_{OC}-values (Tab. II) suffer a stronger fill factor reduction with temperature and display a behaviour similar to that of c-Si cells. It has to be noted here that low-V_{OC} µc-Si:H cells and c-Si cells seem to have a temperature behaviour that hardly varies over a wide range of active cell thickness (from 2 µm up to 300 µm!). For high-V_{OC} µc-Si:H cells, on the other hand, we observe a distinct advantage of working with low cell thicknesses.

If we compare the temperature behaviour of the FF for all three types of single-junction cells, following observations can be made:

(i) In the case of a-Si:H and μc-Si:H the temperature dependency of the FF is not always linear, as is for the case of c-Si.

(ii) For the normalised TC of the FF defined as

$$\frac{\Delta FF}{\Delta T \cdot FF(25°C)}$$

we find the following hierarchy:

a-Si:H < μc-Si:H • c-Si.

(iii) For microcrystalline cells we find that the appearance of a low TC for the FF is linked to the appearance of a relatively high V_{OC}-value.

From these observations one could speculate that the temperature dependence is linked to the nature of electronic carrier transport prevailing in the device. It may be that drift-dominated transport is less affected by temperature than diffusion-dominated transport, as the extreme examples of amorphous and crystalline could suggest. High-V_{OC} μc-Si:H cells may be more drift-dominated and, thus, less influenced by temperature than low-V_{OC} μc-Si:H cells (which would be more diffusion-dominated). In order to prove this assumption more discriminative experiments are needed.

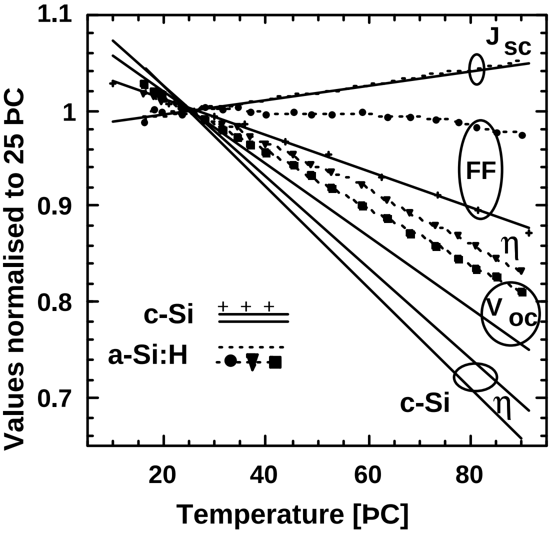

Figure 5: Temperature behaviour of an a-Si:H p-i-n and crystalline silicon solar cells.

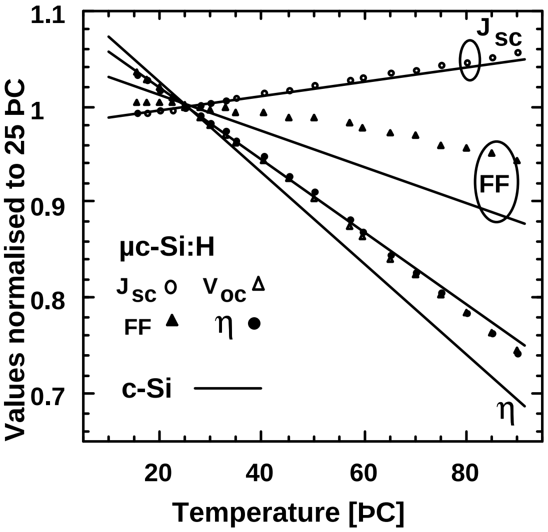

Figure 6: Temperature behaviour of a high-V_{OC} μc-Si:H cell compared with that of a c-Si cell.

Table II: TC-values of the solar cell parameters of the investigated amorphous, crystalline, microcrystalline and micromorph cells. *All TC's are normalised with respect to the values measured at 25 •C, according to the expression (1) given.

Cell	V_{oc}^* [V]	**FF***	$\frac{\Delta V_{oc}}{\Delta T \cdot V_{oc}^*}$	$\frac{\Delta J_{sc}}{\Delta T \cdot J_{sc}^*}$	$\frac{\Delta FF}{\Delta T \cdot FF^*}$	$\frac{\Delta \eta}{\Delta T \cdot \eta^*}$
a-Si:H	0.872	0.711	$-2.9\text{x}10^{-3}$	$7.7\text{x}10^{-4}$	$-2.5\text{x}10^{-4}$	$-2.5\text{x}10^{-3}$
μc-Si:H	0.426	0.549	$-4.8\text{x}10^{-3}$	$5.0\text{x}10^{-4}$	$-1.3\text{x}10^{-3}$	$-5.4\text{x}10^{-3}$
μc-Si:H	0.470	0.675	$-4.2\text{x}10^{-3}$	$5.9\text{x}10^{-4}$	$-1.8\text{x}10^{-3}$	$-5.2\text{x}10^{-3}$
μc-Si:H	0.499	0.651	$-4.0\text{x}10^{-3}$	$6.3\text{x}10^{-4}$	$-1.1\text{x}10^{-3}$	$-4.4\text{x}10^{-3}$
μc-Si:H	0.512	0.659	$-4.2\text{x}10^{-3}$	$6.5\text{x}10^{-4}$	$-9.3\text{x}10^{-4}$	$-4.4\text{x}10^{-3}$
μc-Si:H	0.516	0.676	$-4.0\text{x}10^{-3}$	$7.7\text{x}10^{-4}$	$-6.9\text{x}10^{-4}$	$-4.0\text{x}10^{-3}$
μc-Si:H	0.531	0.698	$-3.9\text{x}10^{-3}$	$8.7\text{x}10^{-4}$	$-7.9\text{x}10^{-4}$	$-3.9\text{x}10^{-3}$
multi c-Si	0.552	0.730	$-3.8\text{x}10^{-3}$	$7.5\text{x}10^{-4}$	$-1.9\text{x}10^{-3}$	$-4.7\text{x}10^{-3}$
mono c-Si	0.538	0.768	$-4.4\text{x}10^{-3}$	$6.4\text{x}10^{-4}$	$-1.7\text{x}10^{-3}$	$-5.3\text{x}10^{-3}$
μ-morph	1.345	0.674	$-3.3\text{x}10^{-3}$	$7.6\text{x}10^{-4}$	$-5.3\text{x}10^{-6}$	$\mathbf{-2.7x10^{-3}}$
μ-morph	1.286	0.711	$-3.5\text{x}10^{-3}$	$7.7\text{x}10^{-4}$	$-3.9\text{x}10^{-4}$	$\mathbf{-3.2x10^{-3}}$
μ-morph	1.287	0.683	$-3.6\text{x}10^{-3}$	$7.8\text{x}10^{-4}$	$-5.8\text{x}10^{-4}$	$\mathbf{-3.5x10^{-3}}$

Due to the fact that the crucial temperature-dependent parameter is the FF, the efficiency of single-junction silicon based solar cells follows the same trend as mentioned in the above observation (ii).

b) Micromorph tandem cells

In the previous section we studied besides the temperature behaviour of the µc-Si:H cells, that of well-established crystalline silicon and amorphous silicon single-junction solar cells. Now, how does the "mixture" of an a-Si:H and a c-Si cells in form of a micromorph tandem cell perform? Do we have to expect a predominately amorphous or a predominately crystalline silicon TC behaviour? At the moment of the present study, only those µc-Si:H bottom cells that have V_{OC}-values around 450 mV were incorporated into micromorph tandems. Therefore, a definitive statement on the temperature behaviour of micromorph tandem cells can not be given as yet. Nevertheless, as shown in Fig. 7, the temperature coefficient of the FF is, in the case of micromorph cells, clearly lower than that for c-Si and also lower than in any single-junction µc-Si:H cell and corresponds more to the tendency observed in amorphous silicon single-junction cells. Thus, the overall TC of the efficiency is, for micromorph cells, clearly below that of (wafer-based) c-Si.

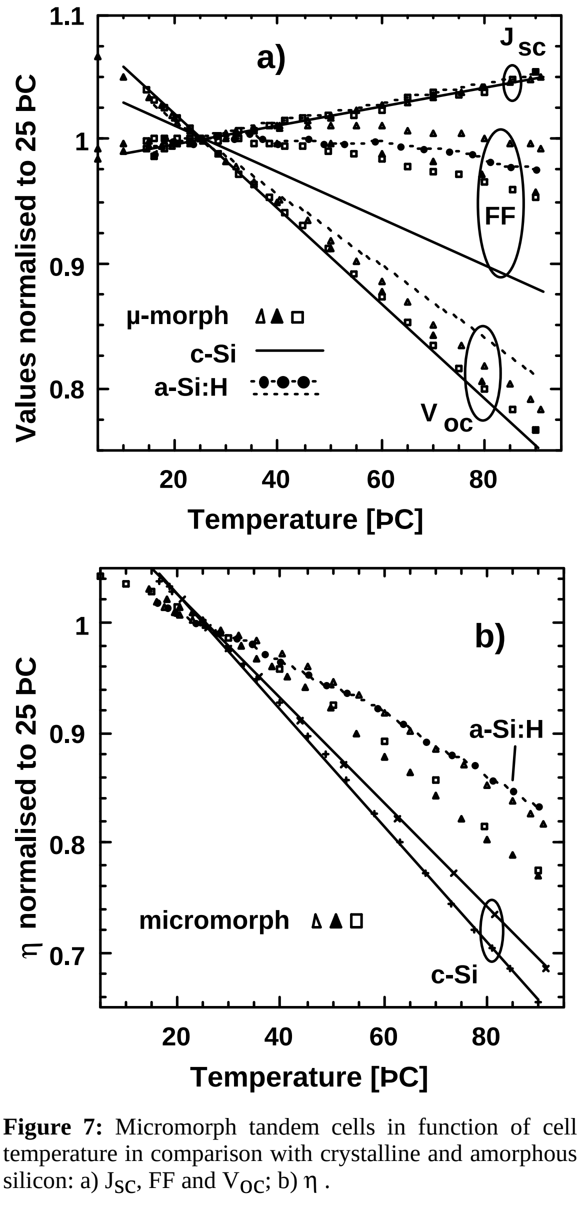

Figure 7: Micromorph tandem cells in function of cell temperature in comparison with crystalline and amorphous silicon: a) J_{SC}, FF and V_{OC}; b) η .

If we consider future micromorph tandem cells with high-V_{OC} bottom cells we can reasonably expect an even lower TC; if confirmed, this would be an important aspect for most outdoor PV applications, as it removes the need for forced-air module ventilation.

4. CONCLUSIONS

Single-junction microcrystalline silicon p-i-n solar cells with open circuit voltages as high as 530 mV and a stable cell efficiency of 8.5 % could be achieved. At present no conclusive statement on the mechanism of the V_{OC} improvement involved in µc-Si:H cells can be given. Laser-scribing, an important key technology for the low-cost thin-film approach (using monolithic series connection), has been successfully applied for thick (3-4 µm) µc-Si cells. In the next step, laser structuring has to be established for the micromorph tandems. If laser-scribing is indeed compatible for micromorph cells a similar impact on cost reduction for module manufacturing, as in the case of amorphous silicon can be expected.

A combination of the hot-wire and VHF-GD deposition technique was found to link the advantages of high deposition rate and the reduced defect density (i.e. device quality) of the µc-Si:H material. In this manner weobtained deposition rates of up to 26 Å/s with low defect densities (comparable to those of VHF-GD material). Such high deposition rates would indeed be desirable for module manufacturing, however, in a next step the quality of this high-rate µc-Si:H would have to be tested in a solar cell device.

A series of different types of silicon based solar cells was studied with respect to their temperature behaviour. We observed that the decisive parameter that governs the TC of the efficiency is the TC of the fill factor. Our recently obtained high-V_{OC} µc-Si:H cells reveal a lower TC of the fill factor as compared with c-Si cells and as compared to our previous low-V_{OC} µc-Si:H cells, as well. Our present micromorph tandem cells, containing sofar only low-V_{OC} bottom cells, show a better thermal behaviour than c-Si and all µc-Si:H cells. The next generation of micromorph tandem cells where we will incorporate µc-Si:H bottom cells having V_{OC}'s > 500 mV should lead to stabilised efficiencies of 13 %. Furthermore, such tandem cells should also have an even better (lower) temperature coefficient. The latter aspect should not be underestimated for real outdoor operations.

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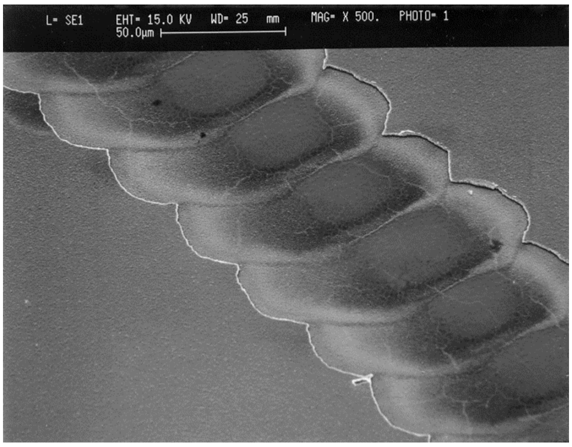
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