

RECENT PROGRESS OF THE "MICROMORPH" TANDEM SOLAR CELLS

D. Fischer, H. Keppner, U. Kroll, P. Torres, J. Meier, R. Platz, S. Dubail, J. A. Anna Selvan, N. Pellaton Vaucher, Y. Ziegler, R. Tscharnner, Ch. Hof, N. Beck, M. Goetz, P. Pernet, M. Goerlitzer, N. Wyrsh, J. Vuille, J. Cuperus, A. Shah;

Institut de Microtechnique, Université de Neuchâtel, rue Breguet 2, CH-2000 Neuchâtel, Switzerland;

Tel: 41 32 718 32 00, Fax: 41 32 718 32 01, E-mail: fischer@imt.unine.ch

<http://www-micromorph.unine.ch>

Abstract: The paper gives an overview over recent results and future potentials of the combined amorphous silicon/microcrystalline silicon "micromorph" tandem cell technology. The reported results include replacement of boron-microdoping compensation by employment of gas-purification to obtain mid-gap microcrystalline silicon, leading to the fabrication of a 3.6 μm thick microcrystalline silicon p-i-n cell with 7.7% stable efficiency. Increased the deposition rate of microcrystalline by $\text{SiH}_4/\text{Ar}/\text{H}_2$ plasma deposition results in a 3.1% efficient microcrystalline single-junction solar cell deposited at 3.0 $\mu\text{m}/\text{hour}$. Further, micromorph tandem cells with 13% initial, or with 10.7% (confirmed by ISE-FhG Freiburg) stabilized efficiency are reported on. The realization of over 13 mA/cm^2 current generation in a 1500 Å thick a-Si:H top cell by combining high temperature deposition and a ZnO intermediate reflector layer demonstrates the potential to yet significantly decrease the top cell degradation in the micromorph tandem cell.

Keywords: Micro Crystalline Si - 1 : a-Si - 2 : Tandem - 3

1. INTRODUCTION

The "micromorph" tandem cell, presented for the first time in 1994, represents an attractive thin film solar cell concept. Enabled by the development of plasma-deposited microcrystalline silicon as an active thin film solar cell absorber material, the combined amorphous/microcrystalline silicon "micromorph" tandem cell has the following interesting properties:

- high efficiency potential by combining a high gap material (amorphous silicon) with a suitable low gap material (microcrystalline silicon)
- potential for low cost fabrication by employment of amorphous silicon type technology (deposition at 200°C, compatible with low-cost substrate materials, monolithic series-connection, etc.)
- all silicon device (no rare, expensive, or toxic materials incorporated)
- short energy payback time through low deposition temperature, and modest silicon requirements (total solar cell thickness $\approx 5\mu\text{m}$)

However, additional efforts are still required before the micromorph tandem cell technology becomes economically feasible. First, the deposition rates of the microcrystalline materials involved, which are currently around 0.5 $\mu\text{m}/\text{hour}$, have to be significantly increased. Secondly, efficiencies should reach a level of at least 12% stable, or higher. Once these requirements fulfilled, the micromorph tandem cell will represent an extremely interesting candidate for large-scale PV module production, with distinct advantages over the competing technologies of a-SiGe:H [1], and of thin film polycrystalline silicon cells [7, 8].

2. MICROCRYSTALLINE SILICON ($\mu\text{c-Si:H}$) AS ACTIVE THIN FILM SOLAR CELL MATERIAL

The $\mu\text{c-Si:H}$ materials investigated in this work are fabricated by glow discharge in a parallel-plate reactor,

employing hydrogen-diluted silane, and plasma excitation frequencies in the VHF-range (Table 1). Otherwise, deposition conditions are identical with those generally used for amorphous silicon deposition. The deposition rates for typical device quality intrinsic $\mu\text{c-Si:H}$ are at around 0.5 $\mu\text{m}/\text{hour}$.

Table 1: Deposition conditions of $\mu\text{c-Si:H}$

hydrogen dilution:	$\text{H}_2:\text{SiH}_4 = 40:1$
plasma excitation frequency:	70-110 MHz
substrate temperature:	170-200°C

Originally, mid-gap $\mu\text{c-Si:H}$ suitable for p-i-n solar cells was obtained by compensation with controlled ppm diborane doping. Later, it was found that mid-gap material can also be obtained by employing gas-purifier to eliminate oxygen from the feedgas [2]. Thanks to this method, which avoids the critical compensation adjust-

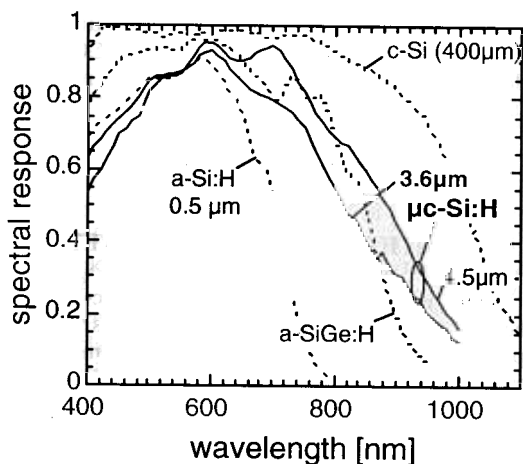


Figure 1: Spectral response of a 3.6 μm thick $\mu\text{c-Si:H}$ p-i-n solar cell (25.4 mA/cm^2). For comparison: a-Si:H p-i-n solar cell; cumulated response of an a-SiGe:H triple cell (26.9 mA/cm^2 , from [1]); crystalline silicon wafer-based solar cell (c-Si); reverse bias response of a 4.5 μm $\mu\text{c-Si:H}$ cell (27.3 mA/cm^2 at -10V bias voltage).

ment, the i-layer thickness of $\mu\text{-Si:H}$ p-i-n solar cells could be increased to beyond $3\ \mu\text{m}$ without compromising the carrier collection. Figures 1 and 2 give the spectral response and the JV-curve of the so far best $\mu\text{-Si:H}$ p-i-n cell having a current density of $25.4\ \text{mA/cm}^2$ and an efficiency of 7.7% [1]. Similar to previous results, this cell again proved to be entirely stable with respect to light-soaking.

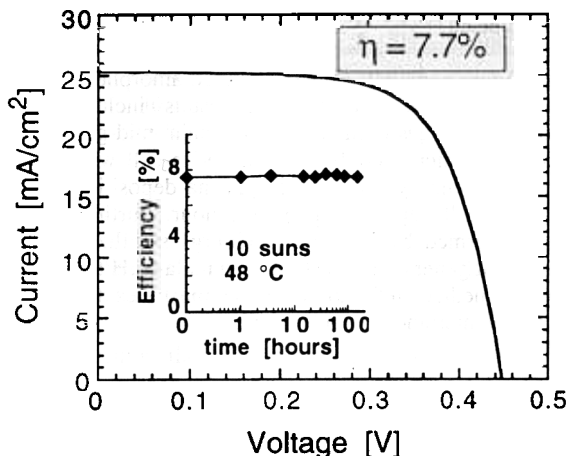


Figure 2: JV-characteristics of a $3.6\ \mu\text{m}$ thick $\mu\text{-Si:H}$ p-i-n solar cell under AM1.5/100mW/cm² conditions (V_{oc} : 448 mV; J_{sc} : 25.4 mA/cm²; FF: 0.68; η : 7.7%). Inset: efficiency during high intensity light-soaking.

Based on the above results, there definitely remains room for some further improvement of the J_{sc} of the $\mu\text{-Si:H}$ solar cells. This thesis is based on the fact that the cell current is at present directly limited by the solar cell thickness. Consequently, the solar cell current is in these devices extremely sensitive to any kind of light-trapping effects (see e.g. also [8]). In the future, a careful optimisation of both external parameters, such as TCO's and back-reflectors, but also of "inherent" light-trapping effects due to material inhomogeneity and/or surface roughness of $\mu\text{-Si:H}$ films (see e.g. [3]), and of the i-layer thickness has definitely the potential to increase J_{sc} towards the region of $30\ \text{mA/cm}^2$. As an illustration, Figure 1 gives the spectral response of a $4.5\ \mu\text{m}$ thick $\mu\text{-Si:H}$ p-i-n cell, deposited on an alternative TCO substrate, yielding a photocurrent of $27.3\ \text{mA/cm}^2$ at reverse bias voltage.

3. DEPOSITION RATE OF $\mu\text{-Si:H}$ MATERIALS

While economically implementing a $\mu\text{-Si:H}$ based solar cell technology, one of the key issues will be the deposition rate of device quality $\mu\text{-Si:H}$ materials. At present the deposition rates of our best $\mu\text{-Si:H}$ materials is definitely too low, but it appears that different possibilities exist to increase the deposition rate [4,5]. A first effort towards higher deposition rates is employing combined Ar/H₂-dilution for $\mu\text{-Si:H}$ deposition [5]. Figure 3 shows how a suitable combination of Ar and hydrogen dilution enables in fact to increase the deposition rate. As a result, a maximal deposition rate of $3.0\ \mu\text{m/hour}$ could so far be obtained. At this deposition

rate, a first single-junction n-i-p $\mu\text{-Si:H}$ cell with 3.1% efficiency was fabricated.

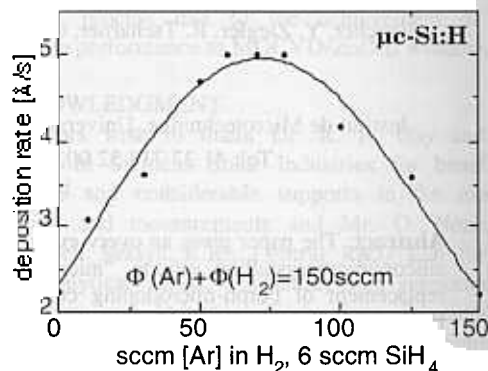


Figure 3: Influence of combined Ar/hydrogen plasma dilution for $\mu\text{-Si:H}$ deposition by VHF-glow discharge at 70 MHz [5].

4. THE "MICROMORPH" TANDEM SOLAR CELL

The most attractive efficiency potential of the microcrystalline solar cells lies in the combination of microcrystalline bottom cells with amorphous silicon (a-Si:H) top cells in the so called "micromorph" tandem cell (Figure 4).

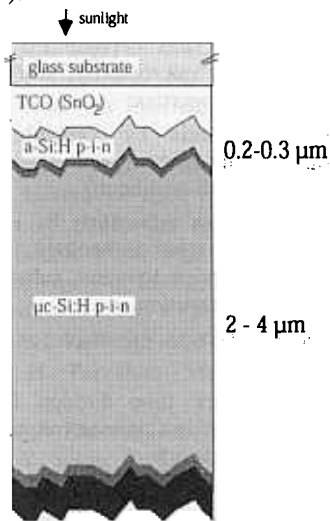


Figure 4: The "micromorph" tandem cell, including an a-Si:H top cell and a $\mu\text{-Si:H}$ bottom cell, deposited by VHF-glow discharge on TCO-coated glass superstrate

This is because the combination of a gap of 1.75 eV (amorphous silicon), and of about 1 eV (microcrystalline silicon) represents a very favourable spacing over the energy range of the sunlight, allowing for high tandem cell efficiencies. This is illustrated in Figure 5, showing the theoretical potential of 4-terminal tandem cells as a function of top cell gap and bottom cell gap (from [6]).

Due to its amorphous silicon top cell, which in fact produces about 2/3 of the total cell power output, the micromorph tandem cell exhibits some extent of light-induced degradation. Micromorph tandem cells therefore have to be optimized for a maximal efficiency after initial

light-soaking, similar to standard amorphous silicon solar cells. Table 1 gives the results of the best "micromorph" tandem cells so far obtained, in the initial state [1], and after stabilization [4]

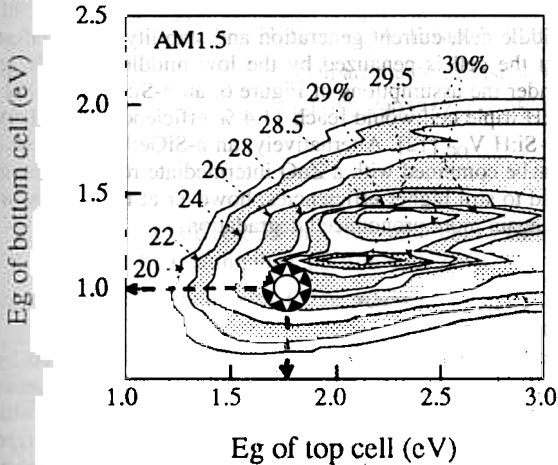


Figure 5: Theoretic efficiencies of 4-terminal tandem cells under AM1.5 conditions (from [6]). The ☼ symbol marks the "micromorph" tandem cell.

Table 2: Efficiencies and JV parameters of significant micromorph tandem cells.

cell, status	η %	J_{sc} mA/cm ²	V_{oc} V	FF %	area cm ²
type A, initial		13.1	1.36		
type B, light-soaked †		11.9	1.34		

†: 1000 hours, 1 sun, 48°C

‡: confirmed by ISE-FhG, Freiburg, Germany

5. TOWARDS HIGHER EFFICIENCIES OF "MICROMORPH" TANDEM CELLS

5.1 Influence of μ -Si:H bottom cell V_{oc}

To become competitive with other thin film technologies, the micromorph solar cells should reach yet higher stable efficiencies. The most direct improvement could result from an increase of the V_{oc} of the μ -Si:H bottom cell. Figure 6 shows the projected effect of an increase in the V_{oc} of μ -Si:H bottom cells on the efficiency of the micromorph tandem cell: In the present tandem cell structure, a V_{oc} of 550 mV in the μ -Si:H bottom cell would rise the efficiency by about 1% absolute. Such voltages have been reached e.g. by SPC poly-Si materials at 550°C [7]. However, it is at this moment not clear by what the V_{oc} of μ -Si:H p-i-n cells is limited, and how it could be improved.

5.2 Current generation and stability of top cells

Regarding the a-Si:H top cells, the difficult task is to combine the required current generation with the best possible stability. For a micromorph tandem cell, 13 mA/cm² is required for the present generation of cells, but even up to 15 mA/cm² might be required in the future. In pure amorphous solar cells, it is not difficult to obtain these currents in relatively stable cells (see Fig. 8). But, as

shown in Figure 8, the lack of a back-reflector behind the amorphous top cell in the micromorph configuration leads to a dramatic decrease of current generation in the amorphous top cell. To obtain 13 mA/cm² with standard amorphous material, an i-layer thickness of about 4000 Å was found to be required. Obviously, such a cell will show a relatively strong light induced degradation. In a first time, it was tried to apply low temperature hydrogen diluted materials in the micromorph top cells. These materials lead to an improved overall stable efficiency in pure amorphous single cells (e.g. [9]). However, the gain in stability is in these cells effected by an increase of the stabilized V_{oc} , at the expense of some reduction in current generation. Consequently, in the context of the micromorph tandem cell, where a high current generation is unavoidable, these materials were found to be in principle less suitable [10]. Nevertheless, the type B cell of Table 2 is based on hydrogen diluted top cell, resulting in a strongly top-limited J_{sc} .

High deposition temperature i-layers: As low gap materials appear more suitable for the micromorph top cell, we started to investigate high deposition temperature materials and top cells. An increase of substrate temperature from 220°C to about 280°C was found to reduce the bandgap by about 30 meV. The influence of this temperature increase on the current generation in single cells and micromorph top cells is illustrated in Figure 8. Details regarding this development will be presented elsewhere [11].

ZnO intermediate reflector layer: Alternatively, the thickness of the top cell can be reduced by the application

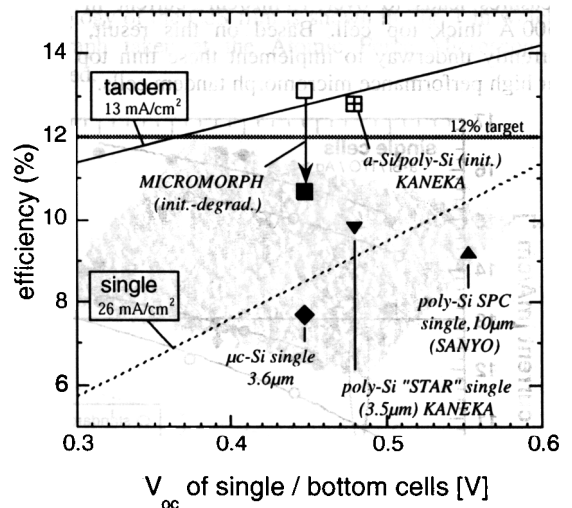


Figure 6: Projected efficiencies of single-junction μ -Si:H, and micromorph tandem cells as a function of the V_{oc} of the μ -Si:H solar cells, assuming a total current of 26 mA/cm², a fill factor of 73%, and a V_{oc} of 900 mV for the a-Si:H cells (lines).

Realized solar cells (symbols):

(◆): μ -Si single cell, 25.4 mA/cm²

(□): micromorph a-Si/ μ -Si, 13.1 mA/cm², initial

(■): micromorph a-Si/ μ -Si, 11.9 mA/cm², stabilized

(▲): p-n cell by solid phase crystallization of a-Si:H on metal, 25 mA/cm² [7]

(▼): n-i-p poly-Si cell by plasma CVD at 550°C, 26.1 mA/cm² [8]

(⊞): stacked poly-Si/a-Si, 13.1 mA/cm², initial [8]

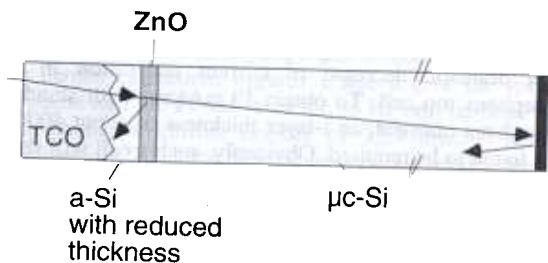


Figure 7: Schematic operation of a ZnO intermediate reflector layer in a "micromorph" double-stacked tandem cell.

of an intermediate ZnO reflector layer between a-Si:H top and μc-Si:H bottom cells [12]. The task of the reflector layer is to achieve a partial reflection of light back into the a-Si:H top cell, allowing thereby to decrease the top cell thickness, and hence to improve its stability (Fig. 7). The reflection effect results from the difference in index of refraction between the ZnO layer ($n=2$) and the surrounding silicon layers ($n \geq 3$).

Most encouraging is the fact that the experimental results show in some cases almost negligible losses in the total absorbed current [12]. This means that a suitable ZnO-layer can achieve a loss-free re-distribution of light absorption towards the a-Si:H top-cell.

Figure 8 shows the influence of high deposition temperature, and of a ZnO reflector layer on the top cell current generation as a function of the i-layer thickness. As a result, the combined application of both measures leads to over 13 mA/cm² current in an only 1500 Å thick top cell. Based on this result, work is currently underway to implement these thin top cells in our high performance micromorph tandem cells.

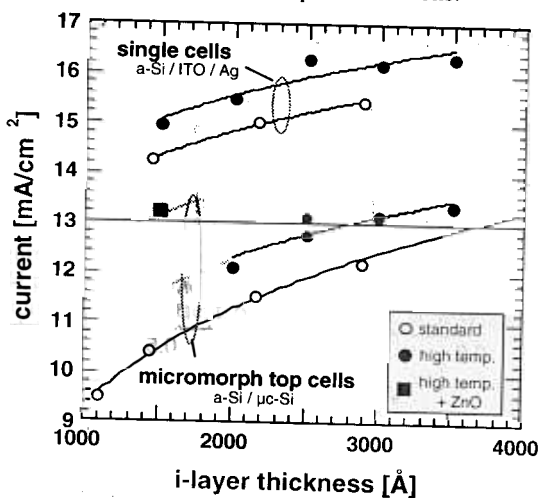


Figure 8: Top cell currents in "micromorph" tandem cells as a function of i-layer thickness, for standard i-layer material (220°C substrate temperature), for high temperature i-layer material (280°C substrate temperature), and for high temperature i-layer material combined with a ZnO intermediate reflector layer.

5.3 Triple-cells

Further efficiency increase could in principle result from a triple cell configuration [12]. In a triple cell the component cell currents would be in a range from 8 to

10 mA/cm². The top cell can thus be designed to be very stable (hydrogen dilution, very thin i-layer, etc.). Regarding the middle cell, again the difficulty resides in combining the required current generation with good stability and the highest possible V_{oc}. With a μc-Si:H middle cell, current generation and stability are manifest, but the cell is penalized by the low middle cell voltage. Under the assumptions of Figure 6, an a-Si:H/μc-Si:H/μc-Si:H triple cell would reach 11.4 % efficiency for 450 mV μc-Si:H V_{oc} [12]. Alternatively, an a-SiGe:H middle cell, maybe combined with a ZnO intermediate reflector, could lead to still higher efficiencies, however at the expense of an again more pronounced degradation.

6. CONCLUSIONS

Microcrystalline silicon p-i-n cells, as deposited by VHF-plasma CVD at 200°C, combine the advantageous fabrication method of amorphous silicon solar cells with device properties similar to thin crystalline silicon type solar cells (stable, approx. 1 eV gap). A stable efficiency of 7.7% is so far obtained on commercial TCO coated glass substrates. Preliminary results of Ar/hydrogen dilution indicate that the major drawback of plasma deposited microcrystalline materials, i.e. an insufficient deposition rate, is not a fundamental obstacle.

The most interesting efficiency potential of microcrystalline solar cells is shown to lie in its combination with an amorphous silicon top cell in a monolithic tandem solar cell. The high efficiency potential of this "micromorph"-tandem cells is confirmed by 13% initial, and 10.7% stable efficiency. Regarding future improvement potentials, considerable room for optimisation is seen in a reduced degradation of the a-Si:H top cell. In this connection it is shown that a ZnO reflector layer between a-Si:H top and μc-Si:H bottom cells, and the application of high temperature deposition can significantly decrease the top cell i-layer thicknesses required to obtain current matched conditions in a micromorph tandem cell. Based on these results, one can conclude that the targeted efficiency of 12% lies within close reach.

Acknowledgements

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