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PROGRESS IN AMORPHOUS AND "MICROMORPH" SILICON SOLAR CELLS

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ABSTRACT: LP-CVD ZnO has been developed at IMT as front TCO for amorphous silicon p-i-n single-junction and "micromorph" (microcrystalline/amorphous silicon) tandem solar cells. In comparison with SnO_2 (Asahi type U), ZnO demonstrates superior light-trapping behaviour. Applying the monolithic series connection by laser-scribing, both for amorphous single-junction and micromorph tandem cells, modules have been fabricated on LP-CVD ZnO. After light-soaking, mini-modules, with an aperture efficiency of 8.5 % in the case of amorphous silicon cells, and of 9.8 % (initial 11%) in the case of micromorph cells, could be obtained. Micromorph tandem cells with an intermediate TCO reflector between the amorphous top and the microcrystalline bottom cell reveal an almost stable performance with respect to light-soaking. A first corresponding module with the applied intermediate TCO reflector could be fabricated.

Keywords: Thin Film, a-Si, Micro Crystalline Si, TCO Transparent Conducting Oxides, ZnO, PECVD

1 INTRODUCTION

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

IMT has, therefore, started developing its own "in-house" zinc oxide, prepared by low pressure chemical vapour deposition (LP-CVD) [1-3]. This specific TCO has notable advantages for thin-film solar cells in general. ZnO itself is an abundant, low-cost material. The LP-CVD method is a simple process with deposition rates of over 20 Å/sec making upscaling to areas of 1m2 easily achievable. The low process temperatures of around 200 °C are entirely compatible with low-cost substrates (polymers, aluminium,..) and the amorphous silicon PECVD (plasma enhanced chemical vapour deposition) fabrication technology.

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

The high photocurrent potential of microcrystalline silicon solar cells can be optimally utilized with the application of an intermediate reflector between the amorphous silicon (a-Si:H) top and the microcrystalline silicon (µc-Si:H) bottom cell. This concept, introduced by IMT in 1996 [8], permits an increase of the a-Si:H top cell current or a reduction of the top a-Si:H cell thickness to improve the stability of the tandem cell. By applying this intermediate TCO reflector concept, Yamamoto et al [9, 10] have recently demonstrated an initial cell efficiency of 14.5 % and declared as a goal the mass production of modules with 12 % efficiency.

Such "modified" micromorph tandem cells have been recently further investigated by IMT.

2 EXPERIMENTAL

The preparation of LP-CVD ZnO has been described in previous studies [1-3]. The ZnO layers were deposited on Schott glass AF45. The a-Si:H p-i-n and micromorph a-Si:H/µc-Si:H tandem solar cells were deposited by VHF-PECVD (Very High Frequency Plasma Enhanced Chemical Vapour Deposition) in a 8x8 cm^2 substrate size laboratory reactor. The deposition rates amounted to 5 Å/s for both the amorphous and the microcrystalline intrinsic layers.

The cells and modules were characterised by an AM1.5 sun simulator (Wacom WXS-140S-10), and test cells were additionally analysed by spectral response measurements. Amorphous silicon single-junction p-i-n test cells were independently characterised by NREL (National Renewable Energy Laboratory, USA).

The stability of test cells and modules was examined under AM1.5 close conditions (1000 h at 0.75/1 sun intensity and 50°C cell temperature).

3 RESULTS AND DISCUSSION

3.1 Amorphous silicon p-i-n test cells

Recently,, we reported [4] on high stable efficiencies of 9 % for a-Si:H p-i-n cells when applying LP-CVD ZnO as front TCO (initial efficiencies close to 11 %). Fig. 1 shows the external quantum efficiency of a typical amorphous p-i-n cell (0.25 µm thickness) deposited on LP-CVD ZnO. This cell was light-soaked over 700 h, however, at an intensity of 0.75 sun instead of one sun. NREL confirmed for this cell an efficiency of 9.5 % (area of 1 cm^2).

3.2 Micromorph silicon tandem test cells

In order to reduce process time and cost we investigated the performance of micromorph tandem cells with µc-Si:H bottom cells of 2 µm thickness using our in-house LP-CVD ZnO as front TCO. Such bottom cells were combined with amorphous top cells. Fig. 2 shows that high initial efficiencies of over 12 % could be achieved, leading to high open circuit voltages of 1.4 volts. After light-soaking (1000 h) these cells show a stabilized efficiency of 10.8 %.

3.3 Intermediate reflector in micromorph tandem cells

The spectral effect of such an intermediate TCO reflector on the a-Si:H top cell is shown in Fig. 3. As initially reported [8], the interlayer improves the top

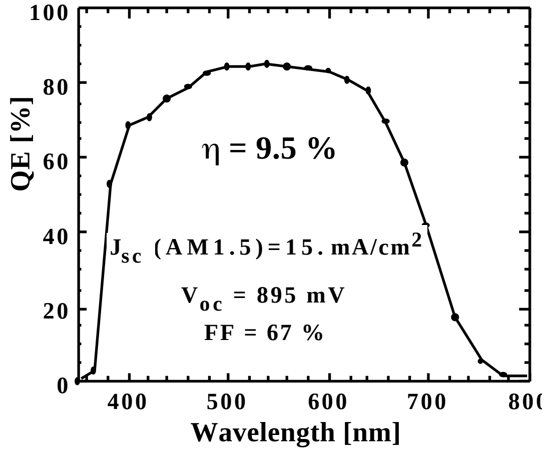

Figure 1: External quantum efficiency of an amorphous p-i-n solar cell of 0.25 µm thickness on LP-CVD ZnO. The values given are deduced from a NREL data of this cell. The cell efficiency of 9.5 % was certified by NREL. This cell was light-soaked during 700 h at 50 °C, however, under 0.75 sun intensity.

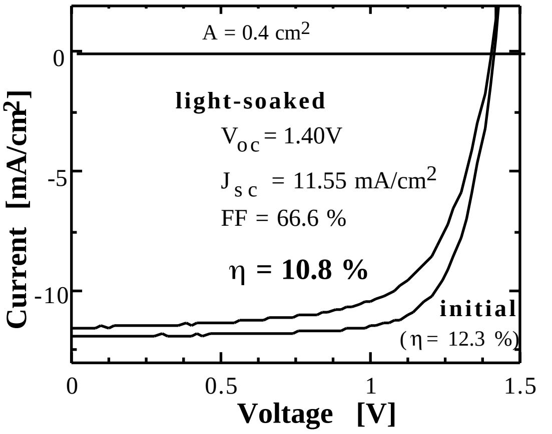

Figure 2: I-V characteristics (AM1.5) of a micromorph tandem test cell on LP-CVD ZnO in the initial state and after 1000 h of light-soaking (1 sun @ 50 °C). The µc-Si:H bottom cell has a thickness of 2 µm.

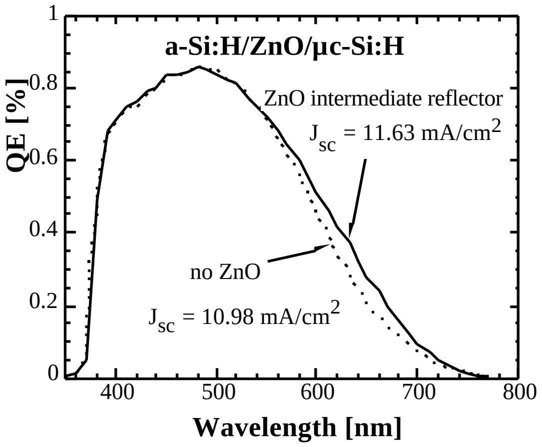

Figure 3: Impact of the intermediate ZnO reflector within the micromorph tandem configuration on the spectral response of the amorphous silicon top cell.

cell photocurrent. In the example of Fig. 3 from approximately 11 to 11.6 mA/cm^2. For the spectral response of the µc-Si:H bottom cell we hitherto observed a higher photocurrent drop that more than offsets the improvement in the a-Si:H top cell. Further investigations with different TCO intermediate layer thicknesses and roughnesses need to be done now.

Examination, under prolonged light-soaking, of tandem cells with an intermediate ZnO layer (Fig. 3) reveals a surprisingly high stability. As Table I reflects, there is no significant change in I-V characteristics after a period of over 1300 h.

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

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

The tandem cell in Table I consists of a very thin a-Si:H top cell (<0.2 µm), which combined with a µc-Si:H bottom cell of only 1.8 µm thickness leads to a large mismatch of the AM1.5 photocurrent (> 1 mA/cm^2). The fill factor is principally affected by the stable µc-Si:H bottom cell and less influenced by small alterations in the a-Si:H top cell (by light-induced degradation).

The conductive TCO interlayer results in the conventional monolithic series connection to a short circuiting of the two component cells. By adding a fourth scribe, we suggest a new interconnection scheme for the segments, as shown in Fig. 4; here, in which the conductive interlayer is separated by the µc-Si:H bottom cell from the back contact.

Proof of concept: In order to check the feasibility of micromorph modules with the intermediate TCO reflector we applied the suggested interconnection of Fig. 4. Hereby, the top and bottom cells involved, as well as the TCO interlayer, were not optimised with respect to high efficiency. The goal was to show whether the series interconnection concept with 4 laser pattern works or not. Results of our first module (Fig. 5, initial state) clearly show that the interconnection scheme as suggested in Fig. 4may be a possible solution to overcome the shunting problem due to the intermediate ZnO reflector in micromorph tandem large-area modules. This 7-segment module possesses a V_{oc}-value that clearly is the sum of the 7 individual open circuit voltages as well as a reasonable fill factor of around 64 %. Further investigations are necessary to improve the I-V characteristics of this type of micromorph modules.

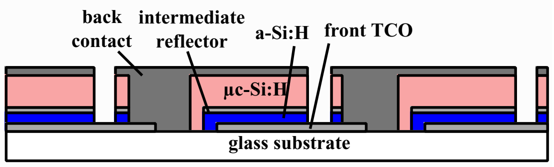

Figure 4: Proposed series interconnection for the micromorph tandem cell module with an intermediate reflector between the a-Si:H top and µc-Si:H bottom cell. 4 scribe pattering are applied instead of 3.

To what extent the efficiency of micromorph tandem cells with intermediate TCO reflectors can be improved while keeping the µc-Si:H bottom cell thin enough is to be seen; furthermore, mass production of micromorph modules with intermediate TCO layers require additional deposition and scribing steps. Particle formation by the laser scribing of the amorphous top cell may cause additional shunting problems, that will yet have to be overcome.

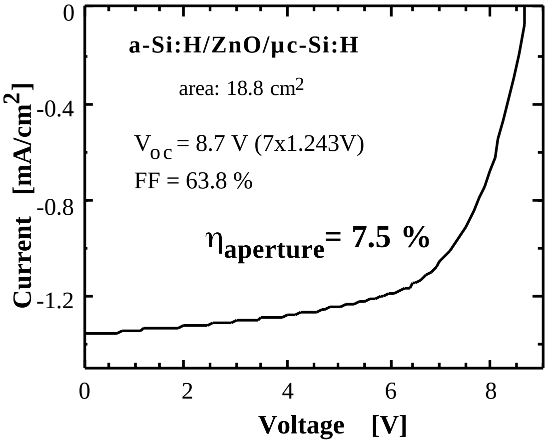

Figure 5: First micromorph mini-module with intermediate ZnO reflector where the series interconnection of Fig. 4 has been applied. Note, the micromorph tandem is here not optimised with respect to interlayer optimisation and with respect to current matching.

3.4 Amorphous silicon modules

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

Fig. 6 shows the AM1.5 I-V characteristics of a 12-segmented module with 24 cm^2 aperture area in the initial and stabilized state (1000 h of light-soaking).

The lower V_{oc}-value in the initial state may be an indication that some interface layers (at the interconnections?) were subsequently improved by light-soaking, a phenomena that is normally not observed in basic test cells. The stabilized aperture module efficiency of 8.5 % shows a surprisingly high potential for the simple amorphous single-junction cell technology, in combination with a high-quality front TCO. Further improvements of our modules can be realized by reducing the scribe losses and improving the monolithic series connection so as to obtain initial fill factors of over 73 %, as usually obtained in test cells.

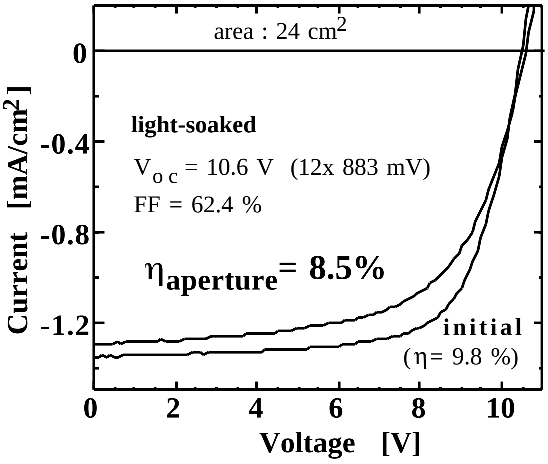

Figure 6: AM1.5 I-V characteristics of a 11-segmented a-Si:H single-junction module based on LP-CVD ZnO as front TCO. The module was light-soaked for 1000 h (1 sun @ 50 ºC).

3.5 Micromorph mini-modules

Such modules have also been fabricated on glass substrates coated with LP-CVD ZnO. The AM1.5 I-V characteristics of a 9-segmented module in the initial and light-soaked (after 1000 h) state is given in Fig. 7.

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

As with the amorphous single-junction module, the micromorph module does not exceed the value of 71 % for its initial FF, whereas test cells show within the deposition area FF values that are typically between 73 and 74 %. The variation of the segment width in the range of 6 to 10 mm does not remarkably affect the FF of both the amorphous single-junction modules, nor that of the micromorph tandem module. We attribute the FF loss of our modules as compared to our test cells, to the monolithic series connection. Improving the FF to values of 73 to 74 % and reducing scribe losses should make stable micromorph modules with over 10 % aperture module efficiency achievable. A further improvement in the micromorph module is now clearly linked with an appropriate choice of the amorphous top cell that is implemented.

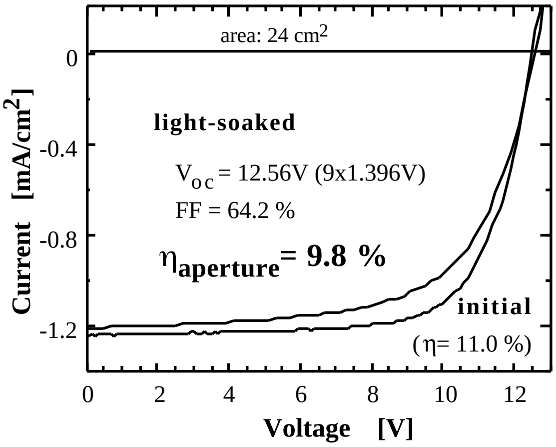

Figure 7: AM1.5 I-V characteristics of a micromorph tandem cell module fabricated on LP-CVD ZnO-coated glass in the initial and light-soaked state. The µc-Si:H bottom cell has a thickness of 2 µm.

4 CONCLUSIONS

In thin-film silicon solar cells with the p-i-n configuration LP-CVD ZnO applied as front-TCO improves light-trapping, as compared to commercially available SnO_2 (Asahi type U). IMT's amorphous single-junction p-i-n solar cell technology was transferred from stable 9 % efficient test cells to mini-modules with a stable aperture module efficiency of 8.5 %, applying thereby the conventional series interconnection technique by laser scribing. This result suggests that the combination of a high-quality TCO with a single-junction amorphous silicon cell allows for the simplification of module manufacturing while sustaining a high efficiency, reducing 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.

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

Micromorph tandem test cells with intermediate ZnO reflector layers between the amorphous top and microcrystalline bottom cell reveal a high stability under prolonged light-soaking. We have achieved already a high stable efficiency of 10.7 %, with a µc-Si:H bottom cell thickness of 1.8 µm, and now a further improvement to values above 12 % is foreseeable at reasonable cell thicknesses. A first module, incorporating our proposed novel interconnection concept, designed to overcome cell short-circuiting due to the intermediate reflector, could successfully be prepared. This first module, that is not yet optimized already shows an initial aperture efficiency of 7.5 %.

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

Acknowledgments

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