

## MICROMORPH SOLAR CELL OPTIMIZATION USING A ZnO LAYER AS INTERMEDIATE REFLECTOR

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### ABSTRACT

The insertion of a zinc oxide (ZnO) intermediate reflector (ZIR) between the top and bottom cell of a superstrate (p-i-n/p-i-n) micromorph tandem solar cell is analyzed, experimentally and by numerical simulation. Solar cells are deposited onto glass plates coated by surface-textured ZnO layers deposited by low-pressure chemical vapour deposition (LP-CVD). The gain in the top cell short-circuit current density ( $J_{sc}$ ) obtained by ZIR insertion as well as the corresponding loss for the bottom cell are experimentally observed, for different values of ZIR thickness  $d$ . The gain and the loss depend nearly linearly on ZIR thickness for  $d < 100$  nm, the maximum gain is almost  $3 \text{ mA/cm}^2$ . Experimental results are compared with an optical simulation. In the latter a three-layer effective media approximation is used for modeling of thin ZIR layers. Micromorph tandem solar cells were deposited on 2 different types of front LP-CVD ZnO layers: (a) a layer optimized for a-Si:H single-junction solar cells; (b) ZnO layers specially developed for  $\mu\text{c-Si:H}$  cells and having undergone a novel surface treatment. In case (a)  $J_{sc} = 12.1 \text{ mA/cm}^2$  and initial conversion efficiency is 11.6 %; in case (b)  $J_{sc} = 12.8 \text{ mA/cm}^2$  and initial conversion efficiency is 11.8 %. The open-circuit voltage ( $V_{oc}$ ) value could be improved from 1.32 V to 1.41 V with an increased surface treatment time.

### INTRODUCTION

The insertion of an intermediate reflector between the amorphous silicon (a-Si:H) top cell and the microcrystalline silicon ( $\mu\text{c-Si:H}$ ) bottom cell of the "micromorph" tandem solar cell [1] increases the value of the top cell short-circuit current density ( $J_{sc}$ ), allowing for a reduction of its thickness and, thereby, for an attenuation of the Staebler-Wronski effect [2,3]. The concept of an intermediate reflector was introduced by IMT in 1996 [2] and was successfully applied by Meier et al. with the demonstration of high stability (over prolonged light soaking) for a bottom-limited micromorph tandems with a thin a-Si:H top cell ( $< 0.2 \mu\text{m}$ ) [4]. It was also applied by Yamamoto et al. who recently demonstrated an initial module efficiency of 13.5 % [5].

In this paper we consider both modeling and experimental results for analyzing the situation and demonstrating how a zinc oxide (ZnO) intermediate reflector (ZIR)

can be used to tune the value of the short-circuit current densities ( $J_{sc}$ ) within a superstrate (p-i-n/p-i-n) micromorph tandem solar cell.

The cell is deposited onto a glass coated with a surface-textured front transparent conductive oxide (TCO). The latter being ZnO fabricated by low pressure chemical vapor deposition (LP-CVD). We compare the performance of micromorph tandem cells integrating a ZIR layer, deposited onto 2 different kinds of front TCO layers: (a) onto our standard LP-CVD ZnO layer optimized for a-Si:H solar cells; (b) onto new LP-CVD ZnO layers specially developed for  $\mu\text{c-Si:H}$  solar cells. These new ZnO layers have a lower free carrier absorption (FCA) and an higher root-mean-square (RMS) value of surface roughness ( $\sigma_{RMS}$ ) than our standard layer [6, 7]. Their surface morphology is, furthermore, modified by a novel surface treatment to render it more suitable for the growth of  $\mu\text{c-Si:H}$  [7]. The effect of this surface treatment is studied for the case of micromorph tandem cells.

### EXPERIMENTAL

#### Device fabrication and characterization

The sheet resistance of the different front LP-CVD layers used in this work is approximately  $10 \Omega/\square$ . Their  $\sigma_{RMS}$  and feature size values were determined by atomic force microscopy (AFM) measurements performed in the non-contact mode.

The ZIR layers deposited here have thickness values ranging from 16 nm to 330 nm and are either ZnO:Al layers deposited by RF-sputtering or LP-CVD ZnO:B layers.

The a-Si:H (180 nm) and  $\mu\text{c-Si:H}$  (1.8  $\mu\text{m}$ ) layers were deposited by very-high frequency plasma enhanced chemical vapor deposition (VHF-PECVD) (see also [8]).

The back contact consists of a LP-CVD ZnO layer covered with a dielectric back reflector. For some experiments the back reflector is not used. The cell area was patterned by laser scribing ( $25 \text{ mm}^2$ ) or by  $\text{SF}_6$  plasma etching ( $\sim 20 \text{ mm}^2$ ).

The current density-voltage (JV) curves were measured using an AM1.5 sun simulator (Wacom). The external quantum efficiencies (EQE) of the top and bottom cells were measured under red and blue bias-light illumination, respectively. Short-circuit current densities for top cell ( $J_{sc,top}$ ) and bottom cell ( $J_{sc,bottom}$ ) were calculated from the EQE curves, by integrating, over the wavelength range,

the product of EQE times the spectral density of the photon flux of AM1.5 solar spectrum.

### Optical modeling

Optical effects of ZIR are studied by means of optical modeling and by calculation of the optical absorption of the various layers within the device. The computer program used includes coherent calculation, scalar scattering theory and Monte Carlo tracing of scattered light [9] as well as experimentally determined wavelength-dependent optical constants [10]. Under the assumption of 100 % collection efficiency, the optical absorption in the top and bottom absorbers permits us to determine the projected increase and decrease in  $J_{sc,top}$  and  $J_{sc,bottom}$ , respectively, as caused by ZIR insertion (designated as  $\delta J_{sc,top}$  and  $\delta J_{sc,bottom}$ , respectively).

For the textured interfaces, a one-layer effective media approximation (EMA) is used [10]. For a ZIR layer with a thickness value  $d < \sigma_{RMS}$ , a three-layer EMA is used: the a-Si:H / ZIR /  $\mu c$ -Si:H region is subdivided into three zones (1), (2) and (3) of thickness  $d$ ,  $\sigma_{RMS} - d$  and  $d$ , respectively. The volume of zone (1) is occupied by a-Si:H and ZnO, the volume of zone (2) is a mix of the 3 materials and the volume of zone (3) is occupied by ZnO and  $\mu c$ -Si:H. The corresponding effective refractive indexes  $\tilde{n}_1$ ,  $\tilde{n}_2$  and  $\tilde{n}_3$ , are calculated as the weighted sum of the refractive indexes of a-Si:H, ZnO and  $\mu c$ -Si:H. The weighting coefficients are calculated as the volume fractions of these materials in zone (1), (2) and (3), supposing homogenous coverage of the surface by the same pyramidal structures.

## RESULTS

### ZIR thickness-effect for a given type of front ZnO

The ZIR thickness  $d$  was varied from 16 nm to 327 nm inside the tandem cells (without back reflector) deposited on front LP-CVD ZnO layers with a surface roughness  $\sigma_{RMS}$  of approximately 80 nm. The experimental difference in  $J_{sc}$  values obtained with and without the ZIR layer (designated here as  $\Delta J_{sc,top}$  and  $\Delta J_{sc,bottom}$  for the top and bottom cells, respectively) are compared with simulated results in Fig. 1.

The experimental gain  $\Delta J_{sc,top}$  increases with a slope of approximately  $0.03 \text{ mA/cm}^2$  per nm of ZIR thickness. The maximum gain obtained is  $2.8 \text{ mA/cm}^2$  for  $d=110 \text{ nm}$ . For higher  $d$  values,  $\Delta J_{sc,top}$  remains in the range of 1.8 to  $2.8 \text{ mA/cm}^2$ . The experimental loss  $\Delta J_{sc,bottom}$  continuously decreases when  $d$  increases. Assuming a linear approximation for this trend for  $d < 100 \text{ nm}$ , its slope is approximately  $-0.04 \text{ mA/cm}^2$  per nm of ZIR thickness.

### Optical modeling

When  $d$  increases, the simulated gain  $\delta J_{sc,top}$  in the top cell increases up to  $2.3 \text{ mA/cm}^2$ , followed by a saturation for  $d > \sigma_{RMS}$  (80 nm). Reversely, the simulated loss  $\delta J_{sc,bottom}$  in the bottom cell decreases rapidly down to  $-3.4 \text{ mA/cm}^2$  for  $d=80 \text{ nm}$  and then continues to decrease less steeply (see Fig. 1).

One may compare these results with those obtained for flat interfaces (verified experimentally in [3]) which demonstrate the interferential behavior of a flat ZIR but with a gain  $\delta J_{sc,top}$  always smaller than the one obtained for rough interfaces (see Fig. 1).

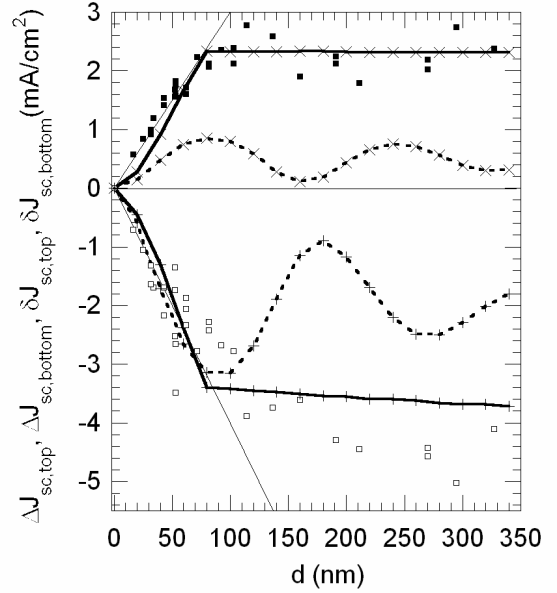


Fig. 1. Experimental gain  $\Delta J_{sc,top}$  (closed squares) and loss  $\Delta J_{sc,bottom}$  (open squares) in the current densities of top and bottom cells, respectively, as a function of ZIR thickness  $d$ . The full lines correspond to the simulated gain  $\delta J_{sc,top}$  (x) and loss  $\delta J_{sc,bottom}$  (+) for rough interfaces and the dashed lines correspond to the simulated results for the case of the flat interfaces. The two continuous hair-lines indicate the slopes ( $0.03 \text{ mA/cm}^2$  and  $-0.04 \text{ mA/cm}^2$  per nm) observed experimentally for small values of  $d$ .

### Roughness and feature size effect

We observed previously that the experimental gain  $\Delta J_{sc,top}$  and loss  $\Delta J_{sc,bottom}$  obtained by insertion of a 30 nm thick ZIR remain constant ( $1.0 \text{ mA/cm}^2$  and  $-1.4 \text{ mA/cm}^2$ , respectively) when the  $\sigma_{RMS}$  value of the front LP-CVD ZnO layer varies from 60 nm to 109 nm [8]. The effectiveness of thin ZIR is therefore not affected by interfaces roughness with  $\sigma_{RMS}$  values between these two limits.

With our novel surface treatment for LP-CVD ZnO layers [7] it is now possible to successfully deposit micromorph tandem cells on rougher front TCO layers, without incurring dramatic losses in open-circuit voltage ( $V_{oc}$ ) and fill-factor (FF) [11]. Micromorph tandems deposited on 2 strongly different front LP-CVD ZnO layers with  $\sigma_{RMS}$  values of 69 and 276 nm and feature sizes of 360 nm and  $1.05 \mu\text{m}$ , respectively, are compared in Fig. 2. In both cases a 90 nm thick ZIR layer is inserted and a back reflector is used. When the tandem is deposited onto the highly-textured front TCO,  $J_{sc,top}$  decreases from  $12.4$  to  $10.7 \text{ mA/cm}^2$  ( $-14 \%$ ) and the sum of the  $J_{sc}$  values of top and bottom cells increases from  $22.1 \text{ mA/cm}^2$  to  $23.2$

$\text{mA}/\text{cm}^2$  (+5 %), as compared to the less textured substrate. In this comparison, the very strong increase of surface texture implies a 14 % reduction in  $J_{\text{sc,top}}$ , corresponding to a decrease of the top cell EQE in the 500-750 nm spectral range (see Fig. 2).

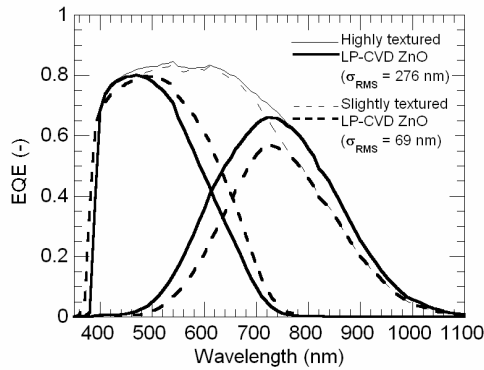


Fig. 2. Comparison of EQE curves of a-Si:H top and  $\mu\text{c-Si:H}$  bottom cells of micromorph tandems with a 90 nm thick ZIR layer and back reflector. The tandems are deposited on two different front TCO layers, with  $\sigma_{\text{RMS}}$  values of 69 nm and 276 nm. One finds:  $J_{\text{sc,top}}=12.4 \text{ mA}/\text{cm}^2$ ,  $J_{\text{sc,bottom}}=9.7 \text{ mA}/\text{cm}^2$  for slightly-textured TCO and  $J_{\text{sc,top}}=10.7 \text{ mA}/\text{cm}^2$ ,  $J_{\text{sc,bottom}}=12.5 \text{ mA}/\text{cm}^2$  for highly-textured TCO.

#### Front LP-CVD ZnO surface treatment

Single-junction p-i-n a-Si:H solar cells with 180 nm thick intrinsic layers were deposited onto front LP-CVD ZnO layers specially developed for  $\mu\text{c-Si:H}$  p-i-n solar cells, thereby employing different surface treatment times.  $V_{\text{oc}}$  and FF of the a-Si:H cells improved with the duration of the treatment, while  $J_{\text{sc}}$  decreased. Without surface treatment, the values of  $V_{\text{oc}}$ , FF and  $J_{\text{sc}}$  were 868 mV, 72.3 % and  $15.18 \text{ mA}/\text{cm}^2$ , respectively. By applying a 60 minute surface treatment to the front LP-CVD ZnO layer,  $V_{\text{oc}}$  and FF increased to 927 mV and 75.1 %, respectively, while  $J_{\text{sc}}$  decreased to  $14.65 \text{ mA}/\text{cm}^2$ . The initial conversion efficiency is thereby improved from 9.5 % to 10.2 % by the surface treatment of 60 minutes' duration (Table 1).

Treatment time (min)	Single-junction a-Si:H				Micromorph $V_{\text{oc}}$ (mV)
	FF (%)	$V_{\text{oc}}$ (mV)	$J_{\text{sc}}$ ( $\text{mA}/\text{cm}^2$ )	Eff (%)	
0	72.3	868	15.2	9.54	1322
20	75.0	896	14.8	9.95	1392
30	-	-	-	-	1411
40	74.8	909	14.6	9.93	-
60	75.1	927	14.6	10.2	-

Table 1. Electrical characteristics of single-junction a-Si:H solar cells and  $V_{\text{oc}}$  values of micromorph tandem cells with a novel surface treatment used on the front LP-CVD ZnO, for different durations of the surface treatment (0 minute stands for "no surface treatment").

In the micromorph configuration, both the top and bottom cells benefit by the favorable surface morphology obtained on the front LP-CVD ZnO layer, by our novel surface treatment. The latter is, thus, efficient in increasing  $V_{\text{oc}}$  of micromorph tandem solar cells. Table 1 shows the evolution of the  $V_{\text{oc}}$  values of tandem cells with respect to the duration of the surface treatment. 30 minutes indeed improves  $V_{\text{oc}}$  from 1.32 V to 1.41 V.

The surface treatment influences the tandem current densities: a decrease of  $0.45 \text{ mA}/\text{cm}^2$  in  $J_{\text{sc,top}}$ , and an increase of  $0.26 \text{ mA}/\text{cm}^2$  in  $J_{\text{sc,bottom}}$  were observed for a 40 minute treatment time.

#### Cell optimization

The linear dependence of  $\Delta J_{\text{sc,top}}$  and  $\Delta J_{\text{sc,bottom}}$  with ZIR thickness, experimentally observed for ZIR layers thinner than 100 nm and for front TCO layers with  $\sigma_{\text{RMS}}$  values between 60 and 110 nm, can be used as a design tool to determine the ZIR thickness required to obtain slightly bottom-limited micromorph tandem cells.

With our standard front LP-CVD ZnO layer optimized for a-Si:H solar cells and with top and bottom cell thicknesses of 180 nm and  $1.8 \mu\text{m}$ , respectively, we succeeded, by the insertion of a 50 nm thick ZIR, in obtaining a bottom-limited tandem with  $J_{\text{sc}}=12.1 \text{ mA}/\text{cm}^2$ ,  $V_{\text{oc}}=1315 \text{ mV}$  and  $\text{FF}=73.2 \%$ , yielding an initial conversion efficiency of 11.6 %. The sum of the  $J_{\text{sc}}$  values of this tandem is  $24.5 \text{ mA}/\text{cm}^2$ .

With the new front LP-CVD ZnO layers developed for  $\mu\text{c-Si:H}$  solar cells, the decrease in  $J_{\text{sc,top}}$  value caused by the increased surface texture of the front LP-CVD ZnO (see Fig. 2) and by the novel surface treatment has to be taken into account. By increasing the top and bottom cell thicknesses to 290 nm and  $3.0 \mu\text{m}$ , respectively, and with a short 10 minute surface treatment of the front LP-CVD ZnO, we succeeded, with the insertion of a 50 nm thick ZIR, to obtain a bottom-limited tandem cell with  $J_{\text{sc}}=12.8 \text{ mA}/\text{cm}^2$  (bottom cell  $13.2 \text{ mA}/\text{cm}^2$ ,  $V_{\text{oc}}=1315 \text{ mV}$  and  $\text{FF}=70.2 \%$ , yielding an initial conversion efficiency of 11.8 %. The EQE curves are presented in Fig 3.

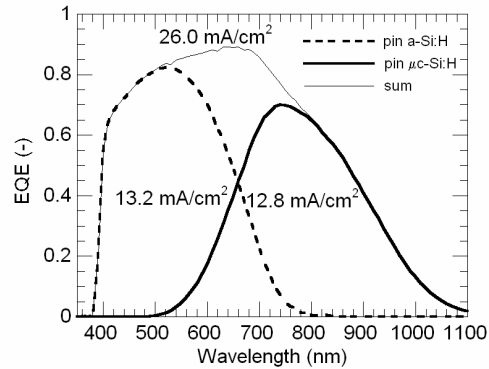


Fig. 3. EQE curves of the top and bottom cells of a micromorph tandem solar cell optimized on the new front LP-CVD ZnO.

## DISCUSSION

### ZIR thickness-effect for a given type of front ZnO

For ZIR thicknesses  $d < 100$  nm, we observed here that the slopes of the linear trends are  $0.03 \text{ mA/cm}^2$  and  $-0.04 \text{ mA/cm}^2$ , respectively, per nm of ZIR thickness. These values are useful for the prediction of the top and bottom current densities when varying  $d$ . A ZIR thickness larger than 100 nm may not be favorable as the loss  $\Delta J_{sc,top}$  then gets continuously larger.

### Optical modeling

The three-layer EMA model for thin ZIR succeeds in predicting a gradual change in  $\delta J_{sc,top}$  and  $\delta J_{sc,bottom}$  when  $d$  increases up to the  $\sigma_{RMS}$  value of the interfaces. The discontinuity obtained when  $d$  reaches the  $\sigma_{RMS}$  value is obviously produced by a discontinuity in the model, since the effective refractive indexes stop changing at this point.

A wavelength-dependent EMA model may be better suited for addressing the situation arising with rough interfaces with large feature size (see next section).

### Roughness and feature size effect

The gain of 5% obtained for the sum of the  $J_{sc}$  values of the tandem with rougher front ZnO surfaces (see Fig. 2) is the consequence of enhanced light-scattering effects in the infrared part of the spectrum. This shows the substantial advantage of using a very rough front TCO for  $\mu\text{-Si:H}$  and micromorph solar cells. The challenge here is to overcome the reduction observed for  $J_{sc,top}$  (14 %).

For comparison, single-junction  $\text{a-Si:H}$  solar cells present a  $J_{sc}$  loss of only 5 % when deposited on these highly-textured ZnO layers. This 5 % loss corresponds to a decrease of EQE in the 550-700 nm spectral range, and is probably caused by (i) a decrease in the effective intrinsic absorber thickness when deposited onto a very rough front TCO and (ii) a decrease of the light-trapping capability in the 550-700 nm spectral range when the front TCO has very high feature size value.

In addition to (i) and (ii), another cause must be involved in the 14 % reduction observed for  $J_{sc,top}$ . We suggest that this may be linked to a decrease of the ZIR effectiveness for large  $\sigma_{RMS}$  and feature size values.

### Front LP-CVD ZnO surface treatment

The treatment of the front LP-CVD ZnO is very effective in increasing the  $V_{oc}$  values of micromorph tandem cells, up to 1.41 V.

The decrease in  $J_{sc}$  value observed here for  $\text{a-Si:H}$  single-junction solar cell is caused by a smoothing of the surface roughness with increasing treatment time as measured by AFM. For  $\mu\text{-Si:H}$  single-junction solar cells this decrease in  $J_{sc}$  is also observed [7] but it takes place for treatment time longer than 40 minutes. This explains why, for micromorph tandem cells, the 40 minute treatment time changes the balance between  $J_{sc,top}$  and  $J_{sc,bottom}$ .

## Cell optimization

With the novel front LP-CVD ZnO layers developed for  $\mu\text{-Si:H}$  solar cells, the sum of the top and bottom cell  $J_{sc}$  values is  $26 \text{ mA/cm}^2$  which corresponds to an improvement of 6 % compared to the thinner tandem deposited onto the front TCO layer optimized for  $\text{a-Si:H}$  cells.

Matched current density of  $13 \text{ mA/cm}^2$  is then directly achievable with the new TCO. This value was, at present, achieved with a short treatment time (10 minutes) applied to the LP-CVD ZnO layer.

Further increase of treatment time may possibly further improve the  $V_{oc}$  and FF values and bring, thus, the tandem efficiency over 12 %.

## CONCLUSIONS

The insertion of a ZIR layer provides a controlled gain in the current density of the top cell within a micromorph tandem. The maximum gain is almost  $3 \text{ mA/cm}^2$ . For a micromorph tandem with a thin  $\text{a-Si:H}$  top cell (180 nm) and a  $1.8 \mu\text{m}$  thick  $\mu\text{-Si:H}$  bottom cell, the insertion of the ZIR layer allowed us to achieve a  $J_{sc}$  value of  $12.1 \text{ mA/cm}^2$ .

Using our "novel" front LP-CVD ZnO optimized for  $\mu\text{-Si:H}$  cells, we obtained a  $J_{sc}$  value of  $12.8 \text{ mA/cm}^2$  with a top cell thickness of 290 nm and a bottom cell thickness of  $3.0 \mu\text{m}$ . This yielded an initial conversion efficiency of 11.8 %, with a total current density of  $26 \text{ mA/cm}^2$ .

The new surface treatment applied to the front LP-CVD ZnO layer permitted us to improve the  $V_{oc}$  value from 1.32 V to 1.41 V, for unmatched micromorph tandems. We therefore conclude that we now have all the individual "ingredients" needed to fabricate micromorph tandems with stable conversion efficiencies higher than 12 %.

## ACKNOWLEDGEMENTS

The authors thank the Swiss Federal Energy Office (OFEN) for support under grant 101191; they are indebted to M. Vanecek and J. Springer for providing the optical simulation program.

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