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Advanced light management in Micromorph solar cells

L. Castens*, J. Bailat, S. Benagli, J. Hötzel, D. Borello, J. Steinhauser, B. Dehbozorgi, J. Spitznagel, Y. Djeridane, P-A. Madliger, G. Monteduro, M. Marmelo, G. Androutsopoulos E. Vallat-Sauvain, U. Kroll, J. Meier

Oerlikon Solar-Lab SA, Rue du Puits-Godet 12A, CH-2000 Neuchâtel, Switzerland

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Abstract

In this study recent results of Micromorph thin film silicon tandem cells with n-doped silicon oxide based intermediate reflectors deposited in the KAI-M industrial PECVD reactor are discussed. From the optical analysis of the devices, specific features in the reflection spectrum attributed to the incorporated intermediate reflector can be observed. In particular, the influence of the Transparent Conductive Oxide (TCO) layer roughness on the reflection spectrum of the cells is studied. Compared to commercial SnO_2, reflection losses are reduced and photocurrents are increased by using rougher front TCO-layers like LPCVD-ZnO which should lead to potentially higher efficiencies at same silicon absorber thicknesses. Micromorph tandem cells with intermediate reflector on ZnO leads to 10.18 % efficiency after 1000 h of light-soaking, whereas 10.35 % have been achieved on commercial SnO_2.

Micromorph; Tandem cells; Intermediate reflector layer; LPCVD ZnO

1. Introduction

Thin film silicon Micromorph tandem cells, composed of a top amorphous (a-Si:H) p-i-n cell and a bottom microcrystalline silicon p-i-n (µc-Si:H) cell allow reaching higher initial as well as higher stabilized efficiencies than single-junction cells. They preserve the advantages of thin film silicon technology, such as the possibility of large-area deposition and monolithic series connection. The concept of the Micromorph tandem cells improves the conversion over the whole sunlight spectrum by the combination of a "high-bandgap a-Si:H top cell, that absorbs efficiently visible light and the "low–bandgap" (µc-Si:H) bottom cell that converts efficiently the red and infrared part of the spectrum.

However, efficient multiple-junction devices demand careful engineering to balance the photocurrents of both the top and bottom cell while keeping the a-Si:H top cell rather thin to limit light-induced degradation. Several schemes of advanced light management are used for matching the current of the top and bottom cells while keeping the top cell thickness as thin as possible. The optical path of the light into the active layers of the tandem cell is first

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* Corresponding author. Tel.: +41-32-732-5594; fax: +41-32-732-5581.
E-mail address: lucie.castens@oerlikon.com

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increased by applying a rough transparent conductive oxide (TCO) front contact. The increased optical thickness of the absorbing layers allows the top and bottom cells to be thinner. Secondly, a rough transparent conductive oxide back contact in combination with a white reflector further increases the optical thickness of the μc-Si:H bottom cell. Thirdly, a low-index semi-transparent reflector is deposited between the top and bottom cell to reflect part of the light transmitted through the top cell [1-3]. This approach allows to gain in top cell current and stability. If the tandem cell is not designed carefully, the light reflected by the intermediate layer might not be efficiently absorbed in the top cell and can be reflected out of the device. This loss by reflection should therefore be minimized. In this study is shown, that reflection losses are reduced by applying a rougher LPCVD-ZnO (as-grown) front TCO instead of a less rough, commercial SnO_2.

2. Experimental

The tandem cells presented in this work have been deposited on commercially available SnO_2-coated glasses with a haze factor (diffuse transmission / total transmission) of 7 % as well as on as-grown rougher ZnO substrates produced in-house in a LPCVD (Low Pressure Chemical Vapour Deposition) reactor displaying a haze factor of 13%. Amorphous top cells, microcrystalline bottom cells and silicon oxide based intermediate reflectors have all been fabricated in the Oerlikon KAI-M PECVD (Plasma Enhanced Chemical Vapor Deposition) reactor at at an excitation frequency of 40.68 MHz. The intermediate reflector layers have been recently developed and presented in [4]. I-V characteristics under AM1.5 have been measured with a Wacom dual-source solar simulator. Spectral quantum efficiency (QE) measurements allow insight to the total photocurrent potential, more precisely the sum of top and bottom cell currents (J_{sc}(top) + J_{sc}(bot)), as well as the current mismatch, the difference of top and bottom cell currents (J_{sc}(top) - J_{sc}(bot)) under AM1.5 conditions. To compare the impact of the intermediate reflector on total current and reflection characteristics in the tandem a co-deposited cell without an intermediate reflector is prepared as reference device. For the best cells light-soaking was performed at a temperature of 50ºC under approximately 1000W/m^2 for 1000h. The total reflection characteristics (specular & diffuse) of the tandem cell front side have been analyzed by a Perkin Elmer lambda 950 spectrometer equipped with an integration sphere.

3. Results

3.1. *Optical losses in tandem cells with intermediate reflector*

Table 1 shows the current characteristics obtained by QE of different tandem cells prepared on commercial SnO_2 and in-house LPCVD-ZnO. Cells of series (A or B) consist of cells with identical top cell thicknesses, where the top cell thickness for cells of Serie A is thicker than for cells of Serie B. The Bottom cell thickness is identical for all cells presented in Table 1. Indeed, the bottom cell has been co-deposited on all top cells. Table 1 shows in column 4 the overall current loss with the incorporation of the intermediate reflector.

		Reference cell without interlayer Total current J_1 [mA/cm^2] = J_{sc}(top) + J_{sc}(bot)	**Cell with 50nm interlayer** Total current J_2 [mA/cm^2] = J_{sc}(top) + J_{sc}(bot)	**Difference** Current loss [mA/cm^2]= J_1 - J_2
SnO_2	**Serie A**	19.99	19.19	- 0.8
LPCVD-ZnO	**Serie A**	22.47	22.12	- 0.35
SnO_2	**Serie B**	19.97	19.29	- 0.68
LPCVD-ZnO	**Serie B**	21.89	21.47	- 0.42

Table 1: Impact on current densities determined by QE measurements of tandem cells deposited on SnO_2 and LPCVD ZnO with and without intermediate reflectors incorporated. Top cell thicknesses are identical for same series. Note, the reduction of current (J_1-J_2) due to the interlayer in case of LPCVD-ZnO is less pronounced.

The results in Table 1 indicate that cells on LPCVD ZnO reveal in higher total currents compared to SnO_2 for both series. The current loss due to the intermediate reflector is lower in case of LPCVD ZnO. Thus, the results in Table 1 show that the properties of the front TCO play a fundamental role for light-trapping in amorphous silicon top cells when applying interlayer reflectors.

The spectral reflection properties of tandem cells with and without intermediate reflectors are given in Figure 1 and 2 for SnO_2, respectively LPCVD ZnO as front TCOs. Two different intermediate reflectors of 30nm and 50nm thicknesses have been studied for SnO_2, whereas in case of ZnO an interlayer with 50 nm thickness was implemented.

In Figure 1 the presence of pronounced interference fringes is typical for commercial substrates like SnO_2. The reflection at ~ 650 nm clearly increases for the cell with 30 nm interlayer and gets even more pronounced when the thickness of the intermediate reflector is further enhanced to 50 nm. In comparison, Figure 2 reveals the total reflection of cells deposited on LPCVD-ZnO coated glass substrates. The evaluation with Figure 1 indicates directly that the overall reflection characteristics are in case of ZnO reduced by about 2.5 %. In contrast to SnO_2 the cell with 50 nm intermediate reflector on ZnO has a similar low reflection as the cell without interlayer and only faint interference fringes are observed. Remarkably, the introduction of the intermediate reflector seems to barely increase the reflection in case of LPCVD ZnO.

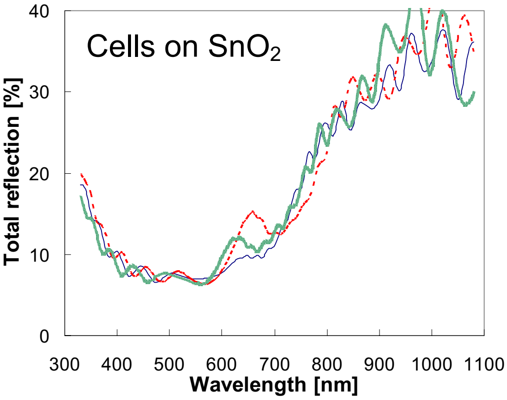

Figure 1: Total reflection spectra (specular & diffuse) of tandem cells deposited on a commercial SnO_2. The three spectra present cells without reflector (black), with an intermediate reflector of 30 nm (green pattern) and with a reflector of 50 nm (red dotted). Compared to the cell without reflector the loss of light at ~ 650 nm wavelength increases with the thickness of the intermediate reflector incorporated.

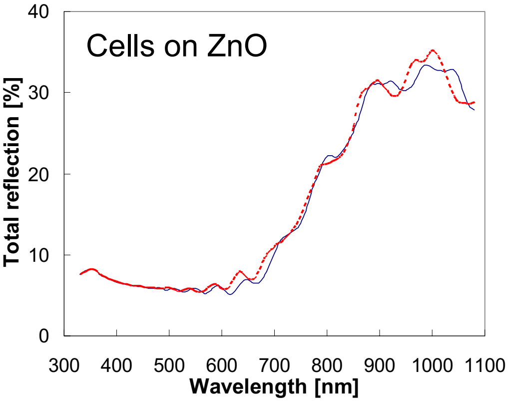

Figure 2: Total reflection spectra of tandem cells deposited on in-house LPCVD-ZnO (higher haze than SnO_2). The two spectra represent cells without intermediate reflector (plain) and with a reflector of 50 nm (dotted). The cell with intermediate reflector does not reveal a clear peak of reflection losses as can be observed on commercial SnO_2

3.2. ***Status of Micromorph cells with intermediate reflector on commercial SnO_2 and on in-house LPCVD-ZnO***

In this chapter results of best a-Si:H/µc-Si:H tandem cells with implemented intermediate reflectors are given both for commercial SnO_2 as well as in-house developed LPCVD ZnO. The detailed solar cell parameters are summarized in Table 2 in the initial and light-soaked state after 1000h.

Up to now, in our laboratory the highest stabilized cells with intermediate reflector on commercial SnO_2 substrates achieved in an initial efficiency of 11.27 % that degraded down to 10.35 % after 1000h of light-soaking [4]. For this slightly bottom limited device the current mismatch in the initial state was 0.57 mA/cm^2 (last column of Table 2). At present for tandems with intermediate reflectors applied on LPCVD ZnO substrates, an initial efficiency of 11.19 % has been reached. This tandem consists of similar top and bottom cell thicknesses as in case of highest stabilized cell on SnO_2. On these so far not fully optimized devices on LPCVD-ZnO the current mismatch is more than twice (1.23 mA/cm^2) than in case of SnO_2. Whereas open-circuit voltage and fill factors are slightly lower compared to SnO_2, short-circuit current is a little higher for ZnO, both in the initial and light-soaked state. Thus, the cell on LPCVD ZnO reaches an efficiency of 10.18 % after 1000h of light-soaking that is very close to the 10.35 % obtained on SnO_2.

Cell with intermediate reflector		V_{oc} [mV]	FF [%]	J_{sc} [mA/cm^2]	Efficiency[%]	Mismatch J_{top}- J_{bot} [mA/cm^2]
Cell on SnO_2	**Initial**	1406	74.58	10.75	11.27	0.57
Cell on SnO_2	**Degraded 1000h**	1381	70.17	10.68	10.35	0.50
Cell on ZnO	**Initial**	1383	72.58	11.15	11.19	1.23
Cell on ZnO	**Degraded 1000h**	1357	68.82	10.90	10.18	1.29

Table 2: Initial and degraded characteristics of tandem cells with intermediate reflector deposited on commercial SnO_2 and on ZnO.

4. Discussion

Our studies above have shown that Micromorph tandem cells on LPCVD-ZnO substrates reveal an overall lower total reflection characteristics compared to SnO_2 which indicates a more efficient light-incoupling to the absorber. Furthermore, in case of SnO_2 as front TCO some additional reflection losses can be attributed to the application of the intermediate reflector visible as increased interference fringes in the reflection spectra (Figure 1). This feature is not observed in the reflection spectra of cells on LPCVD-ZnO (Figure 2). Less pronounced interference fringes suggest again more efficient light-trapping and, thus, a higher current potential for the device. This fact is supported by the devices of Table 1, those reveal higher currents on LPCVD-ZnO. There is a good agreement between the spectroscopic reflection data and the response of the tandem cell devices.

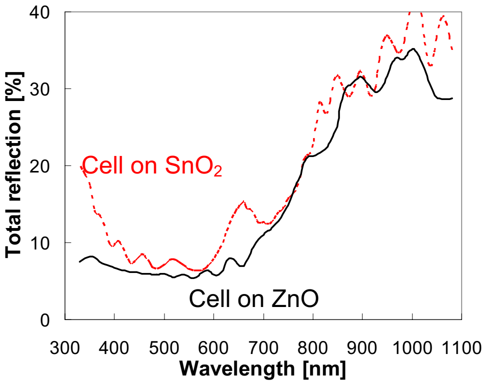

Figure 3: Reflection spectra of Micromorph cells with 50 nm intermediate reflector incorporated. Both tandems consist of same top and same bottom cell thicknesses. The lower curve corresponds to LPCVD ZnO as front TCO, the upper one to SnO_2.

The difference between the amplitudes of the interference fringes in the reflection spectra between 500 and 800 nm of devices on SnO_2 and ZnO (see Figure 3) can be explained by the difference in the intensity of the specular part of light. Indeed, LPCVD-ZnO scatters the incoming light more efficiently (higher haze) and also, we suspect, to higher angles [3]. This results in a decreased amplitude of the observed interference fringes for the solar cell deposited on the rougher LPCVD-ZnO. Furthermore, the rough interface between the LPCVD-ZnO and the cell reacts as a sort of index grading which reduces the overall reflection [5]. In comparison, the smoother SnO_2 coated glass with lower haze has a less pronounced index grading effect. It also transmits more light in the incident direction and, therefore, shows more pronounced interference fringes. As these first results with interlayer and ZnO reveal, the texture of ZnO and its influence on the effectiveness of the intermediate reflector will need further investigations to access higher efficiencies.

On the contrary applying rougher TCO demands some adaptation of the cell deposition processes to obtain good electrical performance of the device, both for amorphous top and microcrystalline bottom cells. Despite the slightly lower FF- and the V_{oc}-values on LPCVD ZnO compared to SnO_2 the efficiency of the Micromorph cell with intermediate reflector after light soaking is similar to the one on commercial TCO. To note is that the similar stabilized efficiency is already achieved with a relatively strongly mismatched tandem cell in case of ZnO.

The details of the gain in top cells due to incorporated intermediate reflectors are not presented in this study. In tendency, however, cells deposited on LPCVD-ZnO reveal a slightly higher gain in top cells than those on SnO_2. Therefore, in combination with the overall enhanced current potential for ZnO (see series A & B above), Micromorph tandems with interlayer should yield in higher stabilized efficiencies on ZnO than on smooth SnO_2. This will be the subject of future investigations.

5. Conclusions

It is shown that the introduction of a silicon-oxide based intermediate reflector in a Micromorph cell on commercial TCO leads to a loss in total current. The total current of tandem cells of same thicknesses deposited on in-house LPCVD-ZnO is higher and results in a smaller loss when an intermediate reflector is introduced. The reflection losses on LPCVD-ZnO are lower and are less influenced by the incorporation of an interlayer.

One can, therefore, suggest that due to enhanced light-trapping of LPCVD ZnO Micromorph tandem cells with intermediate reflectors should lead to higher stabilized efficiencies at same tandem absorber thicknesses than cells on commercial TCOs. Further studies will investigate in more detail the role of LPCVD front ZnO and its surface texture on Micromorph tandem solar cells with intermediate reflectors incorporated.

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