LIGHT MANAGEMENT IN TANDEM CELLS BY AN INTERMEDIATE REFLECTOR LAYER

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ABSTRACT: Recently, it was demonstrated that the insertion of TCO layers between the compound cells of tandem cells allows a shift of current generation from the bottom to the top cell [1]. This concept is particularly useful to increase the performance of a-Si:H/µc-Si:H tandem cells. In this paper we analyse experimental and optical modelling results of very different tandem cell structures in order to assess the full potential of the intermediate reflector concept. Whereas the wavelength response of the reflector is found to be well explained by coherent reflection at the TCO layer, the magnitude of current generation is found to be a strong function of texturing effects.

Keywords: Tandem - 1: Micro Crystalline Si - 2: TCO Transparent Conducting Oxides - 3

1. INTRODUCTION

Thin-film two-terminal tandem cells, combining amorphous silicon top, and micro- or poly-crystalline silicon bottom cells, have recently claimed considerable attention [2], [3]. The advantage of such a tandem cell technology over each of the two individual single cells lies in its high efficiency potential, resulting from the combination of two bandgaps (1.7eV and 1.1eV) that are almost ideally spaced over the interesting part of the solar spectrum, combined with the stability w.r.t. light soaking of the bottom cells, if fabricated in the "correct" manner.

In this type of tandem cells, a problem arises however from the current-matching constraints of the two-terminal approach. With increasing total current generation capacity of the bottom cells, it becomes, in fact and more and more difficult to design a sufficiently stable amorphous silicon top cell that can match the current of the bottom cell. At a level of 30mA/cm² total current generation (this being a realistic expectation for future thin film microcrystalline silicon bottom cells) it can be estimated that only the use of amorphous silicon-germanium alloys, or the use of triple cells, can resolve the current-matching problem.

In this work, we present an alternative solution to achieve current matching, without introducing silicon-germanium alloys; our solution is based on the insertion of a TCO reflective layer between the two component cells.

2. EXPERIMENTAL

This study concentrates on the use of a ZnO intermediate layer in micromorph tandem cells of both substrate- (nipnip) and superstrate- (pinpin) types. For comparison purposes, some have more been conducted on a-Si:H/a-Si:H substrate-type tandem cells. For the optical measurements reported hereunder and conducted on flat surfaces, we investigated test cells consisting of a-Si:H single junction cells deposited on ZnO-covered crystalline silicon wafers.

ZnO layers were deposited by RF-sputtering. All cells were prepared on Asahi type U TCO, by VHF-GD in single-chamber reactors, at 70MHz for a-Si:H cells and in the range 70-130MHz for microcrystalline cells.

Currents in top and bottom cells are evaluated from spectral response (SR). Total SR and total current are the addition of top- and bottom-cell SR, rep. currents. It represents the total generation in the tandem cell and, thus, is the double of the equilibrated tandem current.

3. RESULTS AND DISCUSSION

The principle of the intermediate ZnO (or of any other TCO) reflective layer as used in a tandem cell is sketched in Fig. 1. Reflection results from the difference in refraction index n between the TCO layer (n=2) and the silicon layers (n=3.5-5). The reflected parts of the light at the front and back interfaces are superposed in a coherent manner in the top cell. The reflection is, thus, wavelength-dependent, governed by the ZnO layer thickness. We will study both experimentally and theoretically its exact effect on cells, first in the case of flat surfaces (for comprehension of the basic phenomena), and then in the more realistic case of rough surfaces as used for high efficiency cells.

![Figure 1: Sketch of a micromorph tandem cell with a ZnO reflective layer between top and bottom cell.](image)

3.1 Case of flat surfaces

The relation between the mirror action on the photon distribution in the tandem cell and the ZnO layer thickness is not straightforward. It is governed by a complex interferential combination of the light reflected at all the interfaces involved. For a better understanding of this phenomenon, a simulation model based on matricial calculation of thin films [4] has been developed for the case of flat surfaces [5]. This model calculates the effect of the ZnO layer on the top and bottom cell spectral response curves as well as on the reflection characteristic of the whole cell. Simulation results for substrate-type (nipnip) micromorph tandem cells are compared with measurements performed on optically similar test cells consisting of amorphous nip cells deposited on ZnO-covered crystalline silicon substrates. Fig. 2 presents the influence on the spectral response of a 75nm thick ZnO mirror, both measured and simulated, revealing good agreement between the two. With a 75nm thick ZnO layer, as well as for its odd harmonics (225nm, 375nm, etc.), the interference in the top cell between the portions of light reflected on both sides of the ZnO layer is constructive at 600nm, i.e. where SRtop≈0.5. By choosing these thicknesses, one therefore expect maximum current gains in the top cell.
The shape of the related ΔSR curve, presenting a minimum around 620nm (i.e. where the reflection on the ZnO mirror layer is maximal), is at first glance surprising. Curves for other ZnO layers thicknesses lie all below the curve for 75nm ZnO (Fig. 2, grey lines). The minima are found to correspond to maxima in the related whole cell's spectral response. This highlights the fact that the enhancement in top cell spectral response is a combination of the reflection on the ZnO layer itself and the interference of the not yet absorbed ZnO reflected light with the light reflected on the top TCO. This allows light of certain wavelength, not yet absorbed after a first round trip in the top cell, to be reflected again into the top cell instead of escaping the system. The corresponding photons are, thus, up to a certain point "trapped" in the top cell. Furthermore, such an interference effect can possibly decrease the reflection as compared with the case without ZnO. These "anti reflective" effects depend on a combination of the thicknesses of all layers involved: top TCO, top cell and ZnO mirror.

3.2 Case of rough surfaces

In thin film solar cells, roughness of the different interfaces is well known to lead to large increases of the light absorption. In this section, we will analyse and discuss the influence of roughness on the TCO mirror effect. Top, bottom and total currents of tandem cells as functions of the intermediate ZnO layer thickness are presented in Fig. 5. Cells are of three different types: substrate-type (A) and superstrate-type (B) micromorph (a-Si:H/mic-Si:H), and substrate-type all amorphous (a-Si:H/a-Si:H) (C) (see also Fig 8). A striking observation is that top cell current gains are much higher than in the flat case, up to three times for both types of micromorph cells (two times for the full amorphous cell). This results in an interesting 2mA/cm² current gain for the top cell. The ZnO thickness dependence shows a single sharp maximum around 75nm ZnO, corresponding to the first maximum in the flat case. For thicker reflective layers, top currents increase monotonously.

Bottom current losses stay, for their part, at the same level as for the flat case, meaning that enhanced top gains are not accompanied by a consecutive enhanced reflection at the reflective ZnO layer. For cells of type A with thin (<100nm) ZnO layers, losses are even significantly smaller than in the case of flat surfaces. This fact, combined with the effect of an enhanced top current, means that we could achieve, for the substrate-type micromorph tandem cell, an inversion in the ZnO influence on the tandem total current, resulting in a positive effect on the latter! The ZnO layer inserted in tandem cells has, thus, the capacity of improving the photon injection efficiency into the device whilst thereby strongly enhancing the top cell current.

In Fig 6, spectral responses of the micromorph substrate-type cell with the highest top and total current gains is presented (i.e. with a 75nm thick ZnO layer), agreement is found with currents measured on test cells. For thicker layers, one observes a deviation (i.e. a more pronounced effect for the experimental curves), probably due to slight inherent texture of the thicker ZnO layers. Top current gains are, not surprisingly, accompanied by bottom current losses. As some photons reflected by the ZnO layer are not absorbed in the top cell, losses occur also on the total currents. As shown in Fig. 4, such losses are substantial and could easily counterbalance the advantages obtained by top cell current enhancement thanks to the ZnO layer. Fortunately, we will see in the next section that the situation is much more favourable in the "real" case of rough surfaces.

Figure 2: Effect of a 75nm thick ZnO layer on the spectral response in a test cell (dashed line) and as predicted by the flat surface model (plain line). Grey lines are the predictions for different ZnO thicknesses, ranging from 25 to 800nm. ΔSR=SR(with ZnO layer)-SR(without ZnO layer). Predicted reflections of the whole tandem cell, with and without a 75nm ZnO intermediate layer, are also shown (dotted lines).

Figure 3: Difference in generated current with and without the ZnO reflective layer, as a function of the ZnO layer thickness. Plain line is the prediction of the flat surface model, and dots are experimental results on the test cells; the dotted line represent the "tendency" observed for the test cells (predicted curve, added to a linear influence of ZnO thickness).

Figure 4: Top (dashed line, same as in Fig 3), bottom (dotted line) and total (plain line) currents from simulation as a function of the ZnO reflective layer thickness.
together with the curves for a similar tandem cell but with no reflector layer. The maxima in total SR gain correspond to the minima in the reflection curve shown in Fig 2.

![Graph](image1.png)

Figure 5: Effect of ZnO reflector layers of different thicknesses on top, bottom and total currents for substrate-type (black dots) and superstrate-type (white dots) type micromorph tandem cells, as well as for substrate-type a-Si:H/a-Si:H tandem cell (black triangles). Predictions of the flat surface model are also plotted (black lines, same as Fig 4). For the top cells, experimental results on the flat surfaces test cells are also shown (white squares). Dotted lines are given for the substrate-type micromorph cell and for the a-Si:H/a-Si:H substrate-type top cell, as “guides for the eye”.

![Graph](image2.png)

Figure 6: Spectral responses (top, bottom and total) for substrate-type micromorph tandem cells, with (plain lines) and without (dotted lines) a 75nm ZnO mirror.

Discussion

As illustrated in Fig. 7, the roughness of the interfaces induces diffusion of light inside the tandem cell. At each of the top cell interface, the light is either partly or totally reflected, depending if its angle of incidence is smaller or bigger than the critical angle $\alpha_c$ given by Snell’s law: $\sin \alpha_c = n_{out}/n_{in}$. At the back interface, the critical angle is given by refraction indices of a-Si:H and ZnO and is $\approx 30^\circ$, whether at the top interface, the critical angle is smaller, $\approx 15^\circ$, as the final output medium is air. These angles tend to be larger for longer wavelengths due to the wavelength dependence of the a-Si:H refractive index [6]. Once totally reflected at the back interface, a light ray is, for its specular part at least, trapped in the top cell (playing the role of a wave guide). Corresponding photons have, thus, a strongly enhanced probability to be absorbed and to participate in generating the top cell current. For the part of the light reaching the interfaces with angles smaller than the critical one, description of reflections and transmissions is identical like in the case of flat interfaces.

![Graph](image3.png)

Figure 7: Diffraction of light on the rough interfaces, and total reflection for part of the diffuse light. Refraction indices are $n_0$ for a-Si:H and $n_1$ for TCO’s. R is the reflectance.

Interface roughness, as determined by SEM measurements (not shown here), are sketched for each type of cell in Fig. 8: in cells of type A, it is determined by the sharp, pyramid-like texture of the microcrystalline cell surface, due to the columnar structure of the material. In cells of type B and C, the surface morphology is induced by the TCO substrate surface structure, which is basically similar to that of the thick microcrystalline layer. After the deposition of an amorphous layer, the structure is smoothed and more round-shaped.

![Graph](image4.png)

Figure 8: Sketches of the structure of the tandem cells of type A, B and C considered in Fig. 5. Light comes from the top.

Top cells currents

As diffusion is more pronounced for the rougher interfaces, total reflection is here also more frequent and the top current gain is more important. This explains the observed top current gains: interfaces of the top cell are highly textured, inverted but similar, in type A and B cells, leading to more or less identically high currents; for the cell of type C, interfaces are less rough, and the top current gains are lower.
For thicker ZnO layers, when the thickness becomes comparable to the "texture depth" of the underlying layer, local non-uniformity of ZnO thickness is responsible for the loss of the modulation of the current gain curve vs. ZnO layer thickness.

Bottom cells currents

Bottom current losses are almost not affected by the texture, as the transmission of the ZnO mirror is basically similar like in the flat case. The only significant influence is found in type A cells incorporating thin ZnO layers, whereas such a structure is found at the back interface (TCO in our case) (Fig 9). Even if this event is not of major importance for itself, the multi-impact of the trapped light on this interface could increase its importance for the long wavelengths not absorbed in the top cell. In cells of type A, a sharp relief structure exists at the back interface of the top cell, whereas such a structure is found at the front interface of the top cell in type B cells (Fig. 8) Trapped light with wavelengths not likely to be absorbed in amorphous silicon will then escape preferably toward the bottom cell in cells of type A, and toward the air in cells of type B, explaining the difference in bottom currents.

Figure 9: Description of the "total" reflection effect on rough interfaces

Total currents

The total current is correlated to the reflection of the whole cell. The increase in total current that could be observed in tandem cells thanks to the ZnO layer means that the reflection was decreased. This is due on one hand to the anti-reflection effect of the ZnO layer as described in section 3.1 (not dependant on the roughness), and on the other hand to the decrease of the whole cell reflection contribution from the ZnO mirror reflection as some light is trapped in the top cell (dependant on the roughness).

4. PRACTICAL APPLICATIONS OF TCO INTERMEDIATE REFLECTORS

Thanks to a 75nm thick ZnO layer, in a superstrate-type micromorph tandem cell, the high temperature amorphous silicon top cell thickness could be brought from 250nm to 150nm for a stabilised top current of 13mA/cm² [7]. According to R. Platz’s semi-empirical model for degradation of tandem cells [8], such a reduction of the top cell thickness would lead to a 0.5% absolute gain in stabilised efficiency. For 30mA/cm² total current, the top cell thickness is predicted to be in the range of 250-300nm. As shown above, TCO mirror layers could even be more useful in substrate-type micromorph cells.

5. SUMMARY

Optical modelling based on thin film theory successfully predicts the effect of ZnO intermediate layers on spectral response and reflection of flat interfaces tandem cells. It predicts top current gains ranging between 0 and 0.7mA/cm² depending on the ZnO layer thickness, but accompanied by substantial total current losses.

Diffusion of light occurring at the interfaces of "real" cells with rough surfaces can, thanks to a phenomenon of diffuse light trapping in the top cell, strongly enhance the top current gains, up to 2mA/cm² for the cells considered in this work. Simultaneously, bottom current losses are not enhanced by the diffusion effect, and can even be reduced if the roughness of the interface between top and bottom cells allows the light trapped and not absorbed in the top cell to escape toward the bottom cell. In this case, in fact a global gain in current is observed when a thin internal ZnO mirror layer is inserted.

One can thus conclude that the effectiveness of a TCO mirror layer is deeply liked to the morphology of the cell interfaces, and especially for the interface where the ZnO mirror is inserted. In substrate (nipnip)-type micromorph cells, the interface is governed by the microcrystalline surface structure; using rougher μc-Si:H material could thus enhance the whole effect.

Further work remains to be done in order to demonstrate that the global current gain combined with the decrease of the top cell thickness for a given current can in fact achieve a significant increase in the stabilised efficiency, of about 0.5-0.7% absolute values, in micromorph tandem cells.

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