Presented at 3rd World Conference on Photovoltaic Energy Conversion (WCPEC3), May 11-18, 2003, Osaka, Japan

LIGHT TRAPPING AND OPTICAL LOSSES IN MICROCRYSTALLINE Si AND MICROMORPH SOLAR CELLS

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ABSTRACT

We have developed the 3-dimensional optical model for thin film silicon solar cells (amorphous, microcrystalline, single or multijunction) with nanorough surfaces/interfaces. For these cells the external quantum efficiency, short circuit current, total reflectance and all absorption losses can be computed taking into account roughness, angular distribution of scattered light, thicknesses and experimentally determined optical constants of all layers. The model gives very good agreement with the experimentally determined data for micro-crystalline silicon and micromorph (amorphous-microcrystalline silicon tandem) solar cells. Based on the analysis of optical losses and possible improvements in the materials properties, a roadmap for over 15% stable efficiency of micromorph solar cell has been suggested.

1. INTRODUCTION

Light scattering and trapping in silicon thin films is crucial for a high efficiency of all thin-film silicon solar cells. The reason is the indirect band gap of silicon. Different modeling approaches have been recently applied to this important topic [1-7]. For amorphous or microcrystalline thin film silicon solar cells the nanotextured front transparent conductive oxide (TCO) electrode (with a typical root-mean-square surface roughness of 50-150 nm) and/or nanotextured back reflector have been used. These rough layers can introduce nearly complete diffuse transmission or reflection of light and due to the light trapping in material with high index of refraction (silicon) the optical path of weakly absorbed light is greatly enhanced, leading to higher currents. Quantitatively, this is shown in Fig. 1 for a typical thickness of amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon solar cell.

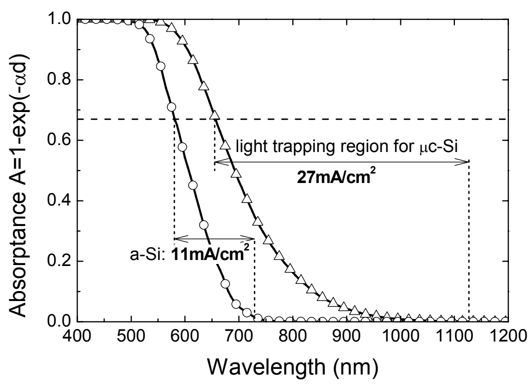

Fig. 1 Light trapping spectral region for typical amorphous (thickness 300 nm) and microcrystalline (2000 nm) silicon solar cell, with the maximal current value, which can be gained in this region.

To calculate an absorption enhancement of random nanotextured solar cells with random roughness and correlation length L smaller than the wavelength λ the simple geometrical optics and usual ray tracing programs [8] cannot be applied. On the other hand, a rigorous coupled wave analysis (except for the case of periodic gratings) is very complicated and time-consuming [2,9]. For these reasons we followed our approach presented at the previous European PV conference [7]. We have also extended our model to 3-dimensional one, as described in details in another paper at this conference [10].

At first, we will review our model, its assumptions and present a new data on direct spectral measurements of absorption losses in rough ZnO/Ag back reflectors. After that we will show under which conditions we can reach over 15 % stable efficiency for thin-film micromorph tandem. Based on comparison of the experimental data and our modeling results we will show that some absorption losses are inherently connected with the light trapping realized by the help of front rough TCO's and rough TCO/metal back reflectors and we will discuss strategies how to reduce these losses.

2. MODEL

In our optical model for the silicon thin film solar cells, the coherent contribution of the multilayer structure is calculated using wave theory taking into account scattering losses at each surface/interface. Then ray tracing of scattered photons is calculated up to the final absorption in any layer of the solar cell or photon loss due to the reflection into air. This is schematically sketched in Fig. 2 for microcrystalline silicon p-i-n cell.

This approach enables us to analyze all optical losses. Monte Carlo method represents an optimal tool to this task. We use experimentally determined optical constants of all materials and experimentally deduced absorption loses in

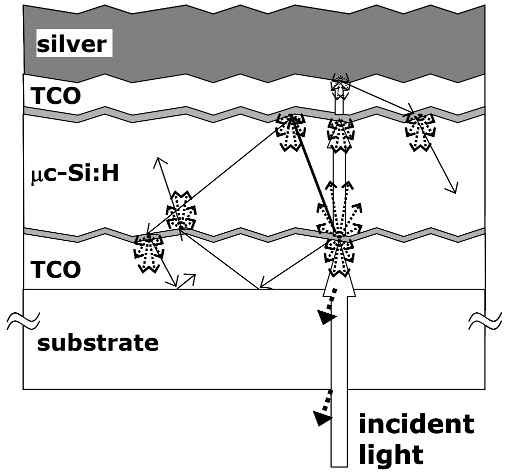

Fig. 2 Schematic sketch of different light paths in the microcrystalline silicon p-i-n solar cell with rough interfaces.

rough ZnO/Ag back reflector, together with typical angular distributions of scattered light at rough surface/interface.

We consider just the photons absorbed in the intrinsic layer of p-i-n or n-i-p cells as contributing to the photogeneration of free electrons and holes. Assuming 100% carrier collection, absorptance in the intrinsic silicon layer equals to the external quantum efficiency (QE). Finally, the short circuit current is obtained by multiplying QE with the AM 1.5 spectrum, 100 mW/cm^2 and elementary charge.

In the optical model we use the following approximations in order to describe the influence of the rough surfaces/interfaces: the effective media approximation (EMA) [11] for description of antireflection properties of rough (graded index of refraction) interfaces and the scalar scattering theory [12].

In p-i-n solar cell (either amorphous or microcrystalline) light enters the silicon absorber layer through glass/ rough transparent conductive oxide (TCO) superstrate. Efficient light scattering at rough TCO (in our case ZnO or commercially available SnO_2)/silicon interface is crucial for a high cell efficiency. It is important to scatter as much of light as possible to the angles larger than the critical angle for total reflection in silicon (outside of so called "escape cone") to get the light trapped in silicon absorber layer. According to the scalar scattering theory an intensity of diffusely transmitted light depends on differences in the refractive indexes of ZnO and Si and on ratio of wavelength to rms surface (interface) roughness (for the case of $L < \lambda$). The angular distribution of scattered light inside the silicon layers has to be measured indirectly [7] and it differs from the angular distribution of transmitted light measured in the system glass/rough ZnO/air and the intensity of diffusely transmitted light also differs.

Now we will concentrate on the combination of amorphous silicon cell with the microcrystalline silicon cell – so called micromorph tandem cell. Schematic sketch of the whole structure is presented in Fig. 3. At the previous European PV Conference we have shown, how our model predicts successfully the behavior of such complex, many-layered structure [7].

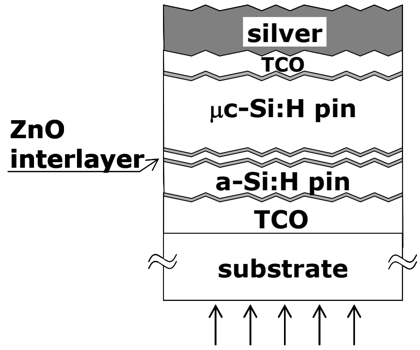

Fig. 3 Micromorph tandem solar cell with an intermediate ZnO reflector between a-Si:H and μc-Si:H cell.

3. ROADMAP FOR OVER 15% STABLE EFFICIENCY OF THE MICROMORPH TANDEM

Present data on efficiency of the micromorph tandem range between 10 – 14.5 %, but this is an initial efficiency [13-15]. While the microcrystalline cell is stable with illumination, the amorphous silicon cell of typical thickness of 250-350 nm exhibits the Staebler-Wronski effect (SWE) and its efficiency stabilizes after one year at a lower value [13].

The reasons for this are the new defects created by light and collapse of internal electric field distribution. To reduce SWE, amorphous silicon layers are deposited at optimal dilution of silane with hydrogen and, simultaneously, the thickness of cell is reduced.

Recently, Neuchatel group reported stable behavior of the whole micromorph cell with thickness reduction of amorphous cell below 200nm [16]. Hence, in our modeling we have taken this thickness as the maximal value, which should guarantee a good stability of the micromorph tandem.

In order to get the stable efficiency over 15% in our model, we can use the optical parameters of the amorphous and microcrystalline silicon absorber which are typical for these materials grown in many laboratories and even in the industrial production (amorphous silicon). The bottleneck is in the supporting layers (front rough TCO, doped p and n layers and in the back reflector. Accepting the following 6 assumptions (which we will discuss later), that

1) front ZnO acts as a ideal Lambertian scatterer, scattering close to 100 % of the incoming light beam intensity
2) simultaneously, absorption loss in ZnO is reduced 3 times in the light trapping region by increasing the electron mobility
3) dielectric back reflector is used with an average reflectance 96-98 %

4) absorption loss in doped layers is reduced 3 times in the light trapping region
5) we use antireflection coatings of glass (double layer on glass, single layer between glass and ZnO)
6) intermediate ZnO reflector between the amorphous and microcrystalline cell compensates for the extremely thin (200 nm) a-Si:H top cell,

we can get the results, presented in Fig. 4. This represents one possibility how to get more than 15 % stable efficiency.

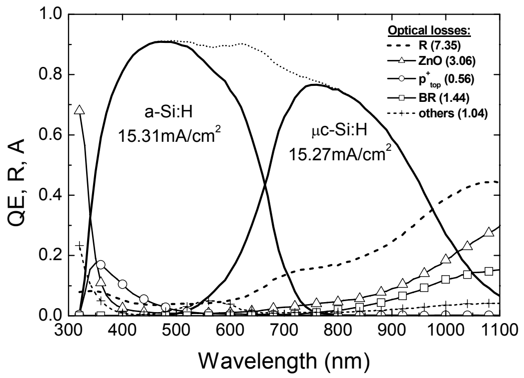

Fig. 4 Optimized micromorph tandem cell with intermediate reflector and efficiency 15.7 % (for realistic fill factor 72 % and open circuit voltage of the tandem 1.43 V). Thickness of a-Si cell is 200 nm, of μc-Si cell 4.4 μm. Main losses (in mA/cm^2) are listed in the upper right corner of the Figure, R being reflection, ZnO is the front TCO, p$^+$ is the front doped layer and BR the back reflector

We can choose yet another approach with the goal to make a *very thin cell*. It translates into a short deposition time, very important for the industrial production and it is also a simpler cell, because it has no intermediate reflector. External quantum efficiency of this alternative micromorph cell can be seen from Fig. 5, thickness of the amorphous cell is again 200 nm and the microcrystalline cell is just 440 nm thin. Under the same assumptions for the FF and V_{oc} as in Fig. 4, the efficiency is still a remarkable 13.6 %.

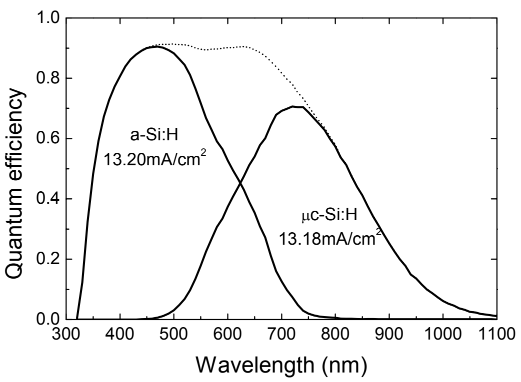

Fig. 5 Micromorph cell with an extremely thin both amorphous (200 nm) and microcrystalline (440 nm) parts and efficiency 13.6 % (for FF=72 % and V_{oc}=1.43 V)

As an alternative to the more complex tandem cell, limits of the single microcrystalline silicon cell, as a function of its thickness are shown in Fig. 6.

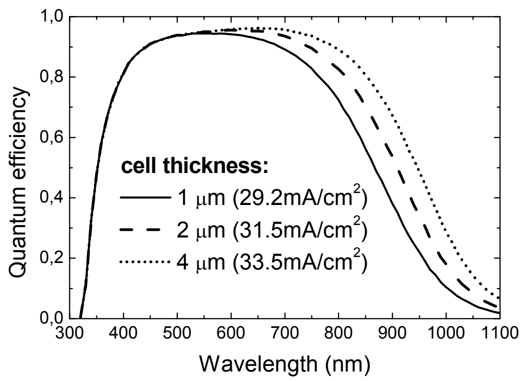

Fig. 6 External quantum efficiency of the microcrystalline silicon single junction p-i-n cell (as in Fig.2), as the function of its thickness and current (mA/cm^2). Corresponding efficiency, under conditions FF=72 % and V_{oc}=0.585 V, is 12.3, 13.3 and 14.1 %.

In the following part we will discuss all our assumptions (1-6) in details.

3.1 Front ZnO

At the present state of development, the most important component for achieving over 15 % stable efficiency of micromorph cell is the quality of the front ZnO in p-i-n type cell. It has to meet 3 important properties: optimal roughness for excellent light scattering, lower optical absorption than the present available TCO's in the light trapping region and good homogeneity of these properties over a large areas.

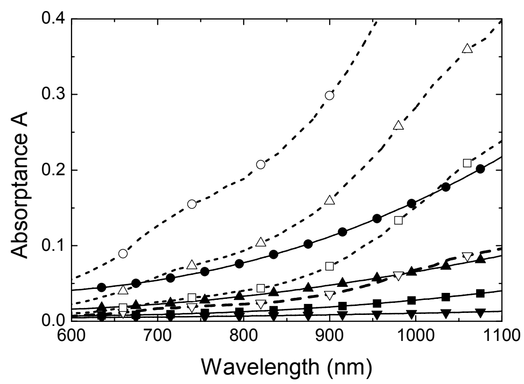

Fig. 7 Absorptance (for thickness of 660 nm of ZnO) as a function of doping – full lines, compared to the absorptance over the average light path in ZnO in the light trapping region – dashed curves

No new discovery is needed in this area to get 15 % stable efficiency, just a very intensive development. This is the area where the research on true thin-film silicon cells (1-2 μm of silicon absorber) should concentrate. In principle, it is possible to raise the present typical electron mobility from about 20 cm^2/Vs to 60 cm^2/Vs and thus reduce infrared absorption while keeping high enough electrical conductivity. Of course, with some breakthrough in this field, the stable efficiency could reach a value over 16%, because the losses in TCO are the dominant ones in the micromorph concept.

To demonstrate how the absorption loss accumulates in the light-trapping region, the Fig. 7 was calculated, using our experimentally determined data (measured by Photothermal deflection spectroscopy). We can directly see that too strong doping accumulates in such a high optical absorption, which cannot be tolerated.

3.2 Back reflector

In the infrared low absorption region most of the light travels through the 200 – 300 nm layer of amorphous silicon and is only partly absorbed in typical 2 μm thick microcrystalline silicon film. Frequently, a thin ZnO/ silver double layer back reflector is used to reflect the light back into the silicon absorber. However, due to the roughness of the underlying layers the back layers forming the back reflector are also rough. This is good for a light scattering and trapping (if the front ZnO is not scattering enough), but this brings an additional light absorption in the rough metal, as we had shown at the previous conference [7].

The reflection at the silver surface is frequently calculated using Ag data from literature and the effect of additional absorption due to silver roughness is usually neglected. We have applied Photothermal deflection spectroscopy (PDS) for direct detailed spectral measurement of absorption loss, as the function of surface morphology [17]. Typical data for rough ZnO (thin)/Ag back reflector are presented in the form of the spectral dependence of reflectance in Fig. 8. We should mention that a direct measurement of absorptance A and calculation of reflectance R = 1 – A is much more precise that a direct measurement of total reflectance (if the reflectance is high enough, as it should be for a good back reflector).

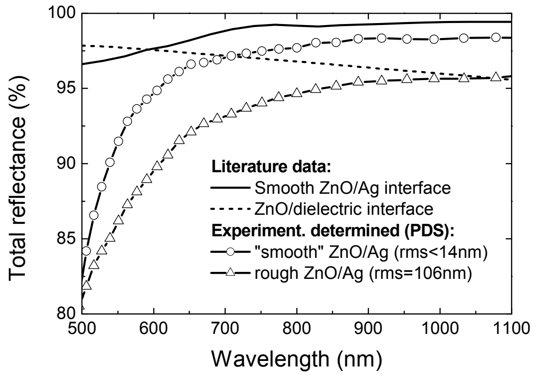

Fig. 8 Reflectance of a typical rough ZnO/Ag back reflector. For comparison, measurement on smooth reflector and data from literature are presented too.

We can conclude that the effect of surface roughness on absorption losses in metal is substantial, especially in the case of rough silver and cannot be avoided. Therefore, we have suggested using a dielectric back reflector. This can be realized either by a very cheap way (white mat paint) or as a sophisticated Bragg reflector (one-dimensional photonic crystal with disorder to increase the spectral range of a high reflectivity).

3.3 Other components

Antireflection coating of glass is the standard industrial process and we will not discuss it here. We should just mention that the nanorough interfaces between silicon and ZnO act as a very efficient antireflection coating due to the index of refraction grading. All this is included in our model.

The light, which is trapped in the silicon absorber is passing through doped p and n layers. Even if the absorption losses here are lower than the typical loss at the front ZnO or at the back reflector, these losses should be reduced. An intensive work is going on in this field (with even a more important topic: how to increase the open circuit voltage by engineering of doped layers and their interface with silicon absorber).

Intermediate ZnO reflector between the amorphous is a crucial component for the cell stability. It reflects light into the amorphous silicon cell, thus making possible to reduce the amorphous silicon thickness and increase stability of the amorphous cell [16].

4. ANALYSIS OF THE EXPERIMENTAL CELL WITH THE HELP OF OUR MODEL.

External QE and reflectance R experimental and model data for amorphous/microcrystalline silicon tandem cell (micromorph cell) are plotted in Fig. 9. This is a thin trial cell for studies with inserted intermediate reflector.

For the tandem cells, the optical modeling is frequently used for current matching of the top and bottom cells. We can measure QE of the top amorphous and the bottom microcrystalline cells separately, with the help of bias blue or dark red illumination.

Looking at Fig. 9 we can analyze the main optical losses for the wavelengths above approximately 650 nm where the light trapping occurs. We can see that for this particular sample the optical absorption in front ZnO layer dominates. This absorption is due to strong free carrier absorption (overdoping). Residual interference effects can be seen because of incomplete light scattering. Even if no antireflection coating is used, reflection is reduced due to antireflective properties of rough interfaces (graded index of refraction). In the region of light trapping the absorption losses in rough Ag backreflector are also seen.

The blue response is influenced by the non-optimized p^+ layer, UV response further by ZnO absorption. On the other hand, losses in undoped back ZnO and in n^+ layer are negligible.

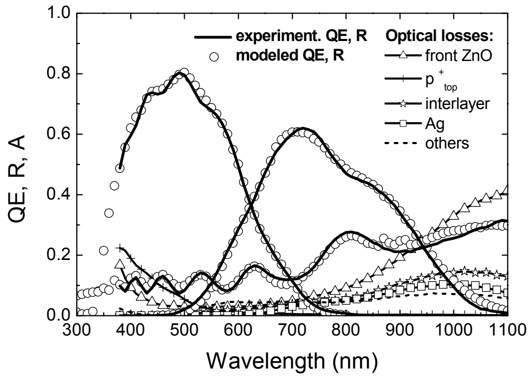

Fig. 9 Experimental and model data for the external quantum efficiency QE and total reflectance R of amorphous/ microcrystalline silicon p-i-n p-i-n tandem solar cell. QE of the top amorphous and bottom microcrystalline cell were measured separately. Absorption losses A at each layer were computed with the help of the model.

There are some problems connected with the absolute measurement of small (<1 cm^2) p-i-n solar cells on a large and thick glass superstrate. Part of the light diffusely scattered back at the front rough TCO/silicon interface is again reflected back at TCO/glass and glass/air interfaces, but outside of the cell area. One-dimensional model does not take this effect into account. Therefore, we have developed the 3-dimensional model [10].

5. CONCLUSIONS

Thin solar cells based on microcrystalline silicon rely on efficient light trapping. The same is true for a more stable amorphous silicon cells (it means very thin cells) and micromorph cells. Our optical model of solar cell gives the ultimate performance of nanotextured thin film solar cell in terms of maximum achievable short circuit current, for a given thickness of all layers and the light scattering parameters of layers and interfaces. It enables us to analyze and identify the losses due to each parameter. Model gives the results within a few minutes on standard PC.

On the basis of our model we have suggested a roadmap for the stable efficiency of micromorph tandem cell over 15%. The quality of amorphous and microcrystalline silicon absorbers, typical for many laboratories, is good enough to get the efficiency over the 15% benchmark. Just the intensive development for up-scaling and the higher deposition rates is necessary.

The bottleneck is in the supporting layers (front rough TCO, doped p and n layers and in the back reflector). Under some realistic assumptions about the front ZnO (being close to the ideal Lambertian scatterer, scattering nearly 100 % of the incoming light beam intensity and, simultaneously, having 3 times reduced optical absorption in the light trapping region) and when the dielectric back reflector is used we can reach this benchmark.

The necessary condition for reaching over 15% *stable* efficiency is the intermediate ZnO reflector between the amorphous and microcrystalline cell, which compensates for the extremely thin (200 nm) a-Si:H top cell. Further requirement is the reduced absorption loss in the doped silicon layers and use of the standard antireflection coating of glass (single layer, from both sides).

ACKNOWLEDGEMENTS

We gratefully acknowledge financial support by RTD Program of the European Community, project "DOIT", contract ENK6-CT-2000-00321.

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