NANOTEXTURED THIN FILM SILICON SOLAR CELLS: OPTICAL MODEL

J. Springer, A. Poruba, A. Fejfar and M. Vanecek*
Institute of Physics, Academy of Sciences of the Czech Republic,
Cukrovarnicka 10, Prague 6, CZ-16253 Czech Republic
* corresponding author, phone ++420 2 20318540, fax ++420 2 3123184, e-mail vanecek@fzu.cz

L. Feitknecht, N. Wyrsch, J. Meier and A. Shah
Institute of Microtechnology, Neuchatel University,
Rue A. L. Breguet 2, CH-2000 Neuchatel, Switzerland

ABSTRACT: Light trapping scheme based on nanotextured surfaces/interfaces of thin film silicon solar cells (amorphous, microcrystalline) deposited on textured ZnO is modeled with the help of Monte Carlo method taking into account the effects of light coherence. Spectral response and short circuit current density are computed as a function of nanoroughness, angular distribution of scattered light, thickness and optical constants of all layers of single or multi-junction solar cells. Simultaneously, optical constants of each layer have been measured. Finally, model results are compared with experimentally determined spectral response of microcrystalline single-junction silicon solar cells.
Keywords: Si-Films – 1: Modeling – 2: Texturization - 3

1. INTRODUCTION

Efficient light trapping is of great importance for thin film silicon solar cells. Recently, a new light trapping scheme based on nanotextured surfaces/interfaces have been introduced [1], which differs from the usual microtextured (textured on the micrometer scale) thick silicon wafers. Internal reflection in a material with a high index of refraction (silicon) and a nanotextured interface (with a random roughness on the scale of tens of nanometers) can lead to complete diffuse reflection of light [2]. The optical path of weakly absorbed light is therefore greatly enhanced.

To calculate an absorption enhancement and the spectral response of nanotextured solar cells geometrical optics cannot be used; therefore, usual ray tracing programs cannot be applied. On the other hand, a rigorous treatment using Maxwell electromagnetic theory (being available only for a periodically repeating surface features) is very complicated and time-consuming [3]. Hence, we have developed a simple Monte Carlo model based on scalar scattering theory, which takes into account the part of light scattered at each interface/surface as well as the coherent part of the non-scattered light in each layer. Either idealized Lambertian distribution of the scattered light or directly measured scattering distribution function is included in our model. Using this method, spectral response (SR) of a single-junction or multi-junction cells can be easily calculated, in a few minutes on a personal computer.

Furthermore, we have measured all optical parameters of each layer of the cells investigated. This is especially important for new materials, as for microcrystalline silicon, or for doped layers where the optical absorption coefficient and the refractive index depend on the doping level. Our model, thus, has no free parameter, since all input data are determined experimentally. We should stress that our model is quite general, not limited to thin film silicon solar cells.

2. MODELING APPROACH

We use the Monte Carlo method for modeling of quantum efficiency (QE) of single-junction or multi-junction solar cell. With an increasing computing power of recent PC's the Monte Carlo method represents an optimal approach to this task. A scheme of the computer program is based on tracing of 20 000 photons for each wavelength. First of all, coherent contribution of the multilayer structure is calculated using wave theory taking into account the scattering losses. 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 enables us to analyze the origin of all optical losses. We consider just the photons absorbed in the intrinsic layer of p-i-n or n-i-p single-junction solar cells as contributing to the photogeneration of free electrons and holes. Finally, the short circuit current is obtained by multiplying SR with the AM 1.5 spectrum, 100 mW/cm^2.

In the optical model we use the following approximations in order to describe the influence of the rough surfaces/interfaces and the bulk light scattering: the scalar scattering theory [4], the effective media approximation (EMA) [5] and the isotropic bulk scattering [5]. Wave theory enables to treat light coherently in thin multilayer structures of solar cells, for tracing of scattered photons geometrical optics is applied. We use experimentally determined optical constants of all materials (exceptions are mentioned in the text) and experimentally determined typical angular distribution of scattered light at rough surface.

3. DETERMINATION OF OPTICAL CONSTANTS

Microcrystalline hydrogenated silicon (μc-Si:H) or alternatively amorphous hydrogenated silicon (a-Si:H) are used as active layers of thin-film solar cells. Optical constants of these layers can be found in the different energy ranges using elipsometry, standard transmittance and reflectance (T/R) spectroscopy, Photothermal Deflection Spectroscopy (PDS) and/or Constant Photocurrent Method (CPM). Although effects of light scattering at rough interfaces are of great importance for achieving high solar cell efficiency, they remarkably complicate the evaluation of all optical parameters. Recently, we have developed procedures how to eliminate such effects from measured T/R, CPM and PDS data [6,7,8]. Fig.1 and 2 show typical data of the spectral dependencies of the absorption coefficient α(E) and the index of refraction n(E) of both amorphous and microcrystalline solar grade materials. It is well known that the bandgap of amorphous silicon depends on the technology and particular deposition conditions. Here we present the data of a-Si:H prepared by standard PECVD (GD) and α(E) and n(E) of microcrystalline silicon grown using the VHF GD technique [9]. One can observe very low defect-connected optical absorption below 1 eV, as typical for a device grade material. Although this part of curves is not usually applied during the modeling (wavelength range from 375 to 1200 nm) it reflects the quality (mainly the defect concentration) of thin films.

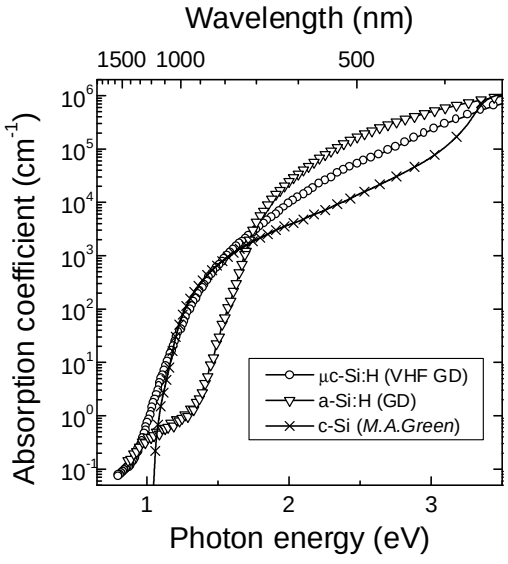

Fig. 1 Measured and evaluated spectral dependencies of the absorption coefficient of microcrystalline silicon (μc-Si:H) and amorphous hydrogenated silicon (a-Si:H); α(E) of crystalline silicon is shown for the comparison [10].

It is obvious that the absorption coefficient of doped material differ mainly in the low energy range due to the enhanced defect concentration and because of free carrier absorption. At the present stage of our model we fix the absorption coefficient at a constant value of around 300 cm^{-1} here. The effects of bandgap shift with doping are taken into account in our modeling, simply by changing the doped layer thickness.

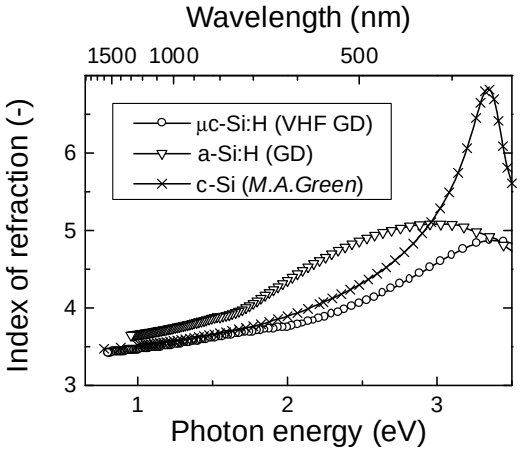

Fig. 2 Measured and evaluated spectral dependencies of the refractive index of microcrystalline silicon (μc-Si:H) and amorphous silicon (a-Si:H); n(E) of crystalline silicon is shown for the comparison [10].

Optical data (α(E) and n(E)) of transparent conductive oxide (TCO) (in our case doped or undoped ZnO) were obtained using T/R spectroscopy and PDS measurements [6,7,8]. Surface roughness of TCO was determined from T/R measurement and checked by AFM. Finally, the optical properties of silver are calculated from data already published [5].

Hence, in the present stage of our model we use the experimental values of optical constant just for undoped microcrystalline and amorphous silicon and for undoped or doped ZnO.

4. MODEL RESULTS AND DISCUSSION

Microcrystalline silicon single-junction n-i-p solar cell structure is shown in Fig. 3.

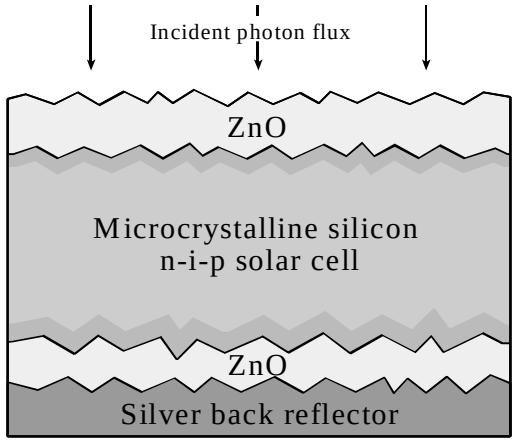

Fig. 3 Sketch of n-i-p thin film solar cell.

Model output has been compared to experimentally measured spectral response (presented as the external quantum efficiency) of fully microcrystalline silicon n-i-p solar cells (with thickness around 2 microns). In our model we assume that all electrons and holes generated in the intrinsic layer of n-i-p are collected. In a particular cell with SR shown in Fig. 4 this case happens at reverse bias of –3 V. Details of solar cell deposition are presented in Ref. 11.

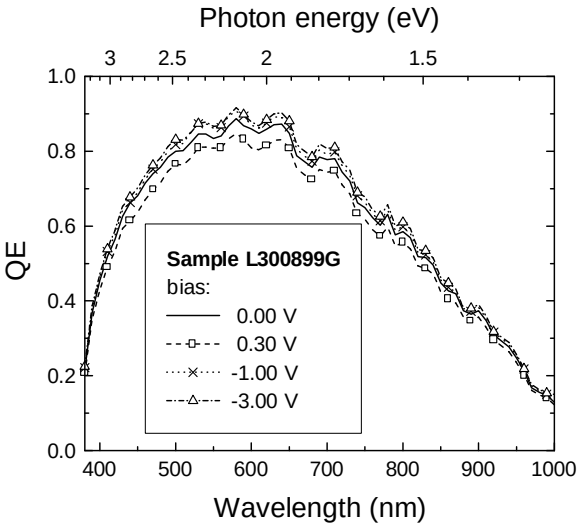

Fig. 4 Quantum efficiency (QE) of the single micro-crystalline silicon solar cell measured with the different bias voltage.

Fig. 5 compares the experimental QE curve (–3V bias) with our model. Very good agreement can be seen, even for all residual interference effects.

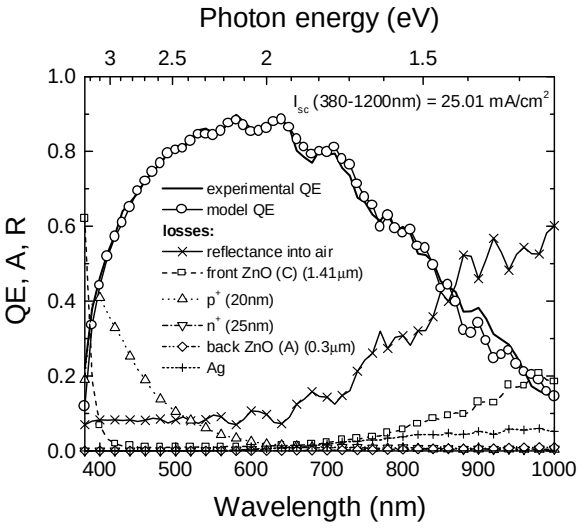

Fig. 5 Measured and modeled quantum efficiency (QE) of the microcrystalline silicon n-i-p solar cell. Optical losses (A) at each layer and reflection (R) of light into the air are also shown.

Fig. 5 allows to analyze where the photons of each wavelength are lost. Reflection losses, absorption in front or back ZnO (they differ in thickness and doping level), in silver backreflector and in p^+ and n^+ layers is directly seen in Fig. 5.

In Fig. 6 we have compared the scattering properties of our experimental 2 microns thin microcrystalline Si n-i-p solar cell [11] with the ultimate scattering properties of ideal Lambertian diffuser. We have plotted I_{sc} as a function of cell thickness. We can see that ideal Lambertian diffuser used just as the backreflector gives the best results.

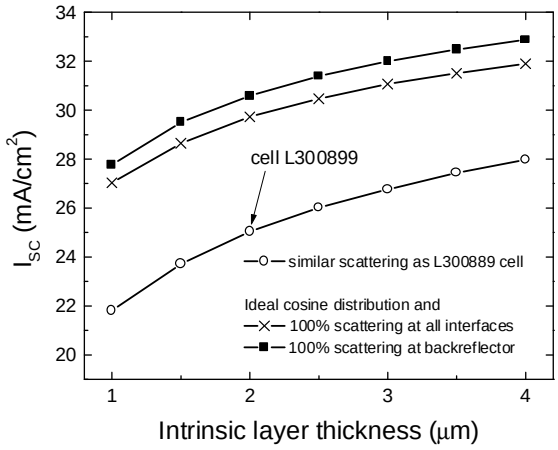

Fig. 6 Comparison of model results of short circuit current I_{sc} for a different cell thickness and scattering properties.

QE model data of amorphous / microcrystalline silicon tandem cell (so-called micromorph cell) are plotted in Fig. 7. Our modeling can be used not only for analysis of optical losses, but also for an optimal current matching between the top amorphous and bottom microcrystalline cell with the surface roughness of each interface used as a parameter.

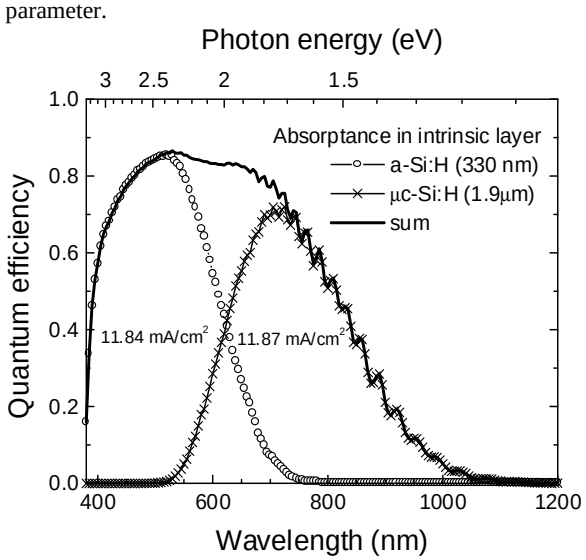

Fig. 7 Model data for quantum efficiency of tandem amorphous / microcrystalline silicon n-i-p n-i-p solar cell.

5. CONCLUSIONS

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. Precise knowledge of optical constants and detailed study of scattering properties is needed in a long wavelength region, where an efficient light trapping is absolutely necessary for the efficient thin-film-silicon solar cells.

REFERENCES

[1] A. Poruba, Z. Remes, J. Fric, M. Vanecek, J. Meier, P. Torres, N. Beck, N. Wyrsch and A. Shah, Proc. 14th European Photovoltaic Solar Energy Conference, Barcelona 1997, p. 2105

[2] A. Poruba, Z. Remes, J. Springer, M. Vanecek, A. Fejfar, J. Kocka, J. Meier, P. Torres and A. Shah, Proc. 2nd WCPSEC, Vienna 1998, p. 781

[3] B.L. Sopori, J. Madjdpour, W. Chen, Proc. 2nd WCPSEC, Vienna 1998, p. 156

[4] P. Beckman, A. Spizzichno, *The Scattering of Electromagnetic Waves from Rough Surfaces*, (Pergamon Press, Oxford 1963), chapter 5

[5] *Handbook of Optics*, 2nd ed., edited by M. Bass (McGraw-Hill, New York, 1995).

[6] M. Vanecek, A. Poruba, Z. Remes, N. Beck, M. Nesladek, J. Non-Crystal. Solids 227-230 (1998) 967

[7] A. Poruba, A. Fejfar, Z. Remeš, J. Špringer, M. Vaněček, J. Kočka, J. Meier, P. Torres and A. Shah, J.Appl.Phys. (July 2000), in print

[8] A. Poruba, A. Fejfar, O. Salyk, M. Vaněček and J. Kočka, J.Non-Cryst.Solids (2000), in print

[9] J. Meier, S. Dubail, J. Cuperus, U. Kroll, R. Platz, P. Torres, J.A. Anna Selvan, P. Pernet, N. Beck, N. Pellaton Vaucher, Ch. Hof, D. Fischer, H. Kepner and A. Shah, J. Non-Crystal. Solids 227-230 (1998) 1250

[10] M. A. Green, *High efficiency silicon solar cells*, (Trans Tech SA, 1987)

[11] L. Feitknecht, O. Kluth, Y. Ziegler, X. Niquille, P. Torres, J. Meier, N. Wyrsch, and A. Shah, this Conference

KEYWORD LIST

Keywords:

Si-Films – 1

Modeling – 2

Texturization - 3