DIFFRACTIVE STRUCTURES FOR ADVANCED LIGHT TRAPPING IN SILICON SOLAR CELLS

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I INTRODUCTION

As an implication of decreasing thicknesses of solar cells, advanced light trapping becomes a key challenge for further development of photovoltaic devices. Even though significant improvements of current solar cells can be achieved by implementing state of the art light trapping techniques [1], for increasingly thin cells more advanced approaches are needed. One promising concept is the application of diffractive backside structures, which can theoretically exhibit optical path length enhancements of a factor of approx. 3000 [2]. This is achieved by diffracting light into directions which are preferably parallel to the solar cell backside. In several previous works (e.g. [3]) the potential of these concepts was demonstrated. The investigation of solar cells with diffractive structures is, however, difficult. In order to achieve an electro-optical description of these cell concepts, we have developed two simulation methods which are discussed in this paper.

II METHODS FOR THE SIMULATION OF SOLAR CELLS WITH DIFFRACTIVE STRUCTURES

As indicated in Figure 1, the backside structures considered in this work exhibit typical dimensions of several hundred nanometers. Thus, in contrast to common wafer-based solar cells, which can be simulated with ray tracing approaches, these concepts require wave optical considerations.

Our first approach uses the rigorous coupled wave analysis (RCWA) to simulate the distribution of the electromagnetic field inside the solar cell. This information is used to calculate an absorption profile $A(z, \lambda)$, which depends on the wavelength and the position along the depth of the solar cell. This absorption profile is finally used as an input parameter for the electrical simulation, which is carried out using the *Sentaurus Device* TCAD software. Further details on the implementation of this method are presented in [4].

This approach provides the complete electro-optical description of both, thin film and wafer-based solar cells with diffractive structures. It is, however, limited to cell geometries without complex frontside textures, which presented the motivation for the development of a second approach described in this paper.

As shown in Figure 1, frontside textures feature typical spatial modulations in the range of ten microns. As a result of numerical limitations, these structures are difficult to address with wave optical methods and thus require ray tracing approaches.

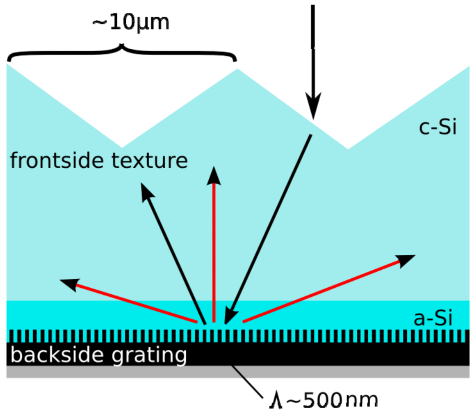

Figure 1: Sketch of a crystalline silicon solar cell with frontside texture and binary backside grating with a period $\Lambda \approx 500$ nm. The black arrows represent the rays in the case of a simple backside reflector. The red arrows indicate additional light paths that arise from the diffraction into higher orders as a consequence of a backside grating.

In order to investigate these cell concepts, we have developed another method which combines the wave optical simulation with a ray tracing approach. This method is implemented by combining the rigorous coupled wave analysis with the ray tracer and the electrical simulation methods included in the *Sentaurus Device* software. In a first step, the diffractive structure is modeled using the RCWA method, which leads to a bidirectional reflectance distribution function (BRDF). This BRDF contains all information required to describe the interaction of a light ray with the diffractive structure. Using an interface provided by *Sentaurus Device*, the BRDF is coupled to a ray tracer, which is used for the optical simulation of the solar cell. The ray tracing algorithm computes an optical carrier generation profile, which finally serves as an input parameter for the subsequent electrical simulation.

The coupling of the wave optical and the ray tracing simulation by means of a bidirectional reflectance distribution function has two major advantages compared to conventional simulation approaches:

1. Due to the combination of wave optical and ray tracing approaches, complex wafer-based solar cell geometries with diffractive structures and regular or stochastic frontside textures such as inverted or random pyramids can be modeled.
2. Even though conventional wave optical methods can be used to simulate cell geometries without frontside textures, their application is limited in practice: every adjustment of a simulation parameter, such as cell thickness or direction of incident light, requires an entirely new wave optical simulation. As the numerical solution of the Maxwell equations has high requirements in terms of computing power, the systematic investigation of these structures using the wave optical method is very time consuming. In contrast, the bidirectional reflectance distribution function, which is used in the coupled method, is independent of the device geometry. Hence, the wave optical calculation of the BRDF has to be performed only once for each diffractive structure. A subsequent variation of device parameters only requires another ray tracing simulation, which usually can be performed very quickly.

In contrast to the method described first, this approach is restricted to solar cells with thicknesses in the range of more than ten microns, which can be modeled using ray tracing algorithms. Thus, certain particular structures remain difficult to simulate; however, with the complementary scope of the two approaches, a broad spectrum of device geometries can be addressed.

III INVESTIGATIONS ON C-SI SOLAR CELLS WITH DIFFRACTIVE BACKSIDE GRATINGS

In order to validate the two approaches and to investigate the potential of diffractive backside structures, we have applied these methods to different kinds of cell geometries. Figure 2 shows the result of the simulation of a 40 µm thick crystalline silicon solar cell with planar frontside and a linear binary backside grating. The comparison of the absorption curves shows very good agreements between the two methods. Further, a significant increase of the number of absorbed photons as a result of the backside grating is demonstrated. This corresponds to an increase in photocurrent density of roughly 2 mA/cm^2 and confirms the positive effect of this light trapping concept.

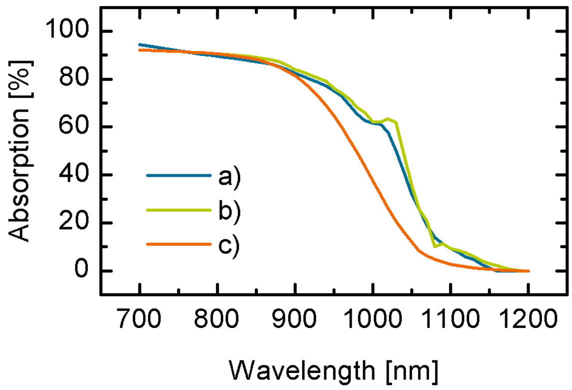

Figure 2: Simulated absorption curves of a 40 µm thick c-Si solar cell with (a, b) and without (c) diffractive backside grating. The grating induces a considerable enhancement in absorption in the long wavelength range. Curve a) was calculated using the wave optical approach, curve b) was generated using the coupled method presented in this work.

IV SUMMARY

In this work we introduced two methods for the complete electro-optical simulation of solar cells with diffractive structures. The first method is based on a wave optical approach, which allows simulation of both, thin film and wafer based solar cells. As this method is restricted to geometries without complex frontside textures, we have presented another approach for the simulation of wafer-based solar cells that combines wave optical and ray tracing approaches. By means of these methods a broad spectrum of device concepts featuring diffractive structures can be investigated. In first results, we achieved good agreement between the two methods and demonstrated positive effects of backside gratings on the optical device properties.

V ACKNOWLEDGEMENTS

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