DIFFRACTIVE GRATINGS IN SOLAR CELLS AND HOW TO MODEL THEM

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Motivation

As solar cells become thinner and thinner, techniques to enhance the path length of light inside the solar cell gain in importance. These techniques can be subsumed under the term "light trapping". A large variety of light trapping concepts exist, ranging from well established to conceptual. An example for a well established concept is the front side texturization of silicon solar cells. Good results have been achieved with pyramidal textures for monocrystalline silicon solar cells [Gre95] or so-called honeycomb textures for multicrystalline silicon solar cells [Sch04]. However, the path length enhancement that can be achieved with a front side texture is limited, and although it is suitable for a silicon solar cell with a thickness of ca. d = 200µm, it is insufficient if the solar cell thickness is reduced to values on the order of 10s of micrometers. The path length enhancement becomes even more crucial for thin film solar cell concepts with thicknesses below 1µm. For such concepts, very efficient light trapping concepts are required that provide a path length enhancement of up to a factor of 100 and more.

A very efficient light trapping, though only in a limited spectral range, is possible by the application of interference effects. Examples here are the application of spectrally or angularly selective elements [Bad09] [Pet09] or diffractive structures [Hei95]. These concepts have currently not developed beyond the laboratory stage. In this work, we will discuss some aspects of diffractive structures that are integrated into silicon solar cells focusing on a method to model such structures.

Diffractive Structures

Diffractive gratings as an application for solar cells were first investigated in the middle of the 1990s [Hei95] but have attracted attention ever since (e.g [Nig02]). The basic idea is to introduce a diffractive element somewhere in the solar cell, preferably at its backside. The diffractive element is meant to diffract light with high diffraction efficiency into an order of diffraction that has a direction preferably parallel to the solar cell backside (see Figure 1). The maximum possible path length enhancement for such an element has been calculated to be approx. L = 3000 in a silicon solar cell [Bad09].

Most concepts investigated in the past aimed for an application in thin film solar cells. Contrary to this, we are currently investigating two kinds of diffractive structures that are introduced into crystalline silicon solar cells. We have several reasons to choose this kind of material:

1- Simulations indicate that with optimized gratings and a combination of front- and backside structures, it is also possible to induce a considerable enhancement in j_{SC} for a thick crystalline silicon solar cell.

2- Crystalline silicon solar cells are the most common solar cells on the market. If a considerable improvement of these cells is achieved with a diffractive grating, a reasonable possibility exists that this technique will be established for industrial applications.

3- Silicon is a very well understood material. This alleviates the investigation of the emerging effects and the development of simulations.

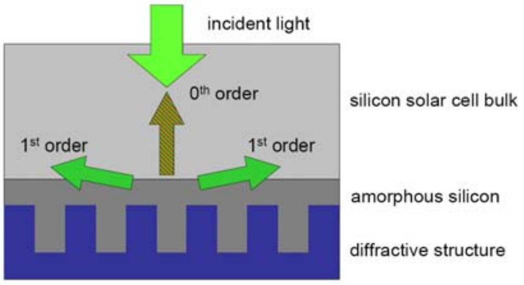

Figure 1:*.Sketch of the concept of a diffractive structure. The figure shows a binary grating. Incident light is diffracted and emitted into several orders of diffraction. Preferably, the first order is emitted into a very steep direction and has a high diffraction efficiency. The diffractive structure is electrically separated from the active part of the solar cell.*

At the moment we are investigating two possible concepts. The first concept is a binary backside grating in combination with a linear front surface texture. The second concept is a 3D photonic crystal backside reflector [Ber07]. In the following we will not discuss the specifics of these concepts, but rather concentrate on several theoretical points that have to be considered when a diffractive structure is introduced into a crystalline silicon solar cell.

First, texturing the backside of a silicon wafer worsens the quality of the backside and enhances recombination there. A grating will therefore have only a positive effect if the enhancement in absorption is not overcompensated by the additional losses due to recombination. To prevent additional recombination, we aim for an electrical separation of the textured region from the electrically active part of the solar cell. Simultaneously we want to keep both regions optically coupled. In the case of the binary grating, we achieve this by depositing a layer of amorphous silicon on the backside of the solar cell, which is electrically inactive, and then texturing the amorphous silicon. Optical coupling is achieved because no difference exists between the refractive indices of textured region and solar cell. In case of the 3D photonic crystal, the diffractive structure is deposited on the back side of the solar cell by a self-organization process in which small PMMA beads adopt an FCC structure. The remaining holes are filled with a high index material which is electrically inactive. Additionally, an electrical passivation layer may be added. Optical coupling is achieved if the refractive index of the filling material is equal or close to that of silicon. As an exemplary material, we are using silicon carbide at the moment.

Second, the optimization of the diffractive grating is a complex process for several reasons. First, solar cells are spectrally broad band devices, whereas diffractive structures typically are optimized for a limited spectral region. Especially for a solar cell with a textured front surface, the effect of a grating might therefore be negative for certain wavelengths. For this reason, the grating effect always has to be considered weighted with the solar spectrum which make calculations time consuming. Second, the quantity of interest of the intended light trapping is the current the solar cell produces. This quantity can only be calculated with considerable effort. Typically, the optical properties of a certain grating are calculated using wave optical methods. These methods, however, do not result in the solar cell current, but rather in diffraction directions and efficiencies and information about the electrical near field. The electrical properties of the solar cell, on the other hand, are typically calculated with simulation methods that use ray tracing, which does not take into account wave optical effects. Our attempt to solve this problem lies in the combination of two simulation methods and is described in the next section.

Simulation Method & First Results

There are several approaches to calculate the effect of a diffractive grating on the performance of a solar cell. In one approach we use a three step procedure. In the first step, we calculate the electrical near field of a solar cell with an integrated grating using the rigorous coupled wave analysis (RCWA). Using this simulation method, we calculate the distribution of the electric field inside the solar cell $E(\vec{x},\lambda)$. Knowing the distribution of the electric field, the absorption distribution can be calculated using the relation

$$Abs(\vec{x},\lambda) \sim | E(\vec{x},\lambda) |^2 \qquad (1)$$

The absorption distribution is a 4-dimensional quantity (three spatial dimensions and wavelength). With a spatial integration, the 2-dimenional absorption profile *Abs(z,λ)* is obtained, which only depends on the wavelength and the position along the depth of the solar cell (see figure 2). Finally, the absorption profile is used as an input parameter for the solar cell simulation tool “Sentaurus Device” to calculate the electrical properties of a solar cell.

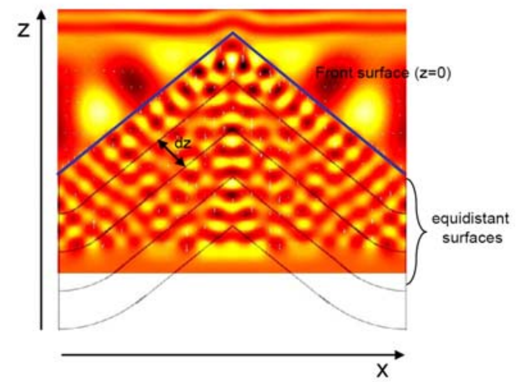

Figure 2: *Distribution of the electric field inside a solar cell with a pyramidal front surface structure, simulated with the RCWA method. To obtain the absorption profile, the intensity is integrated over several layers that are equidistant to the front surface (black lines)*

Using this method we have calculated the effect of a binary grating on the backside of a silicon solar cell with a flat front surface and a thickness of d = 40µm. In this simulation it is assumed that the electrical separation of grating and solar cell was successful and no additional losses occur due to the grating. The result of the calculation is shown in figure 3.

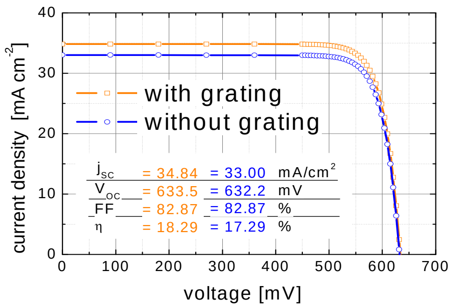

Figure 3: *Result of the electro-optical coupled simulation method. Shown are the IV curves of a solar cell with (orange) and without (blue) a backside diffractive grating. The solar cell with grating shows an efficiency increase of 1% absolute.*

In another approach, the far field characteristics of the grating are calculated using the RCWA method. The electrical characteristics of the solar cell are calculated subsequently using ray tracing. Also used is an FDTD approach instead of RCWA.

Summary

In summary, we have shortly discussed some aspects about the integration of diffractive gratings into crystalline silicon solar cells. One aspect here is an electrical separation and a simultaneous optical coupling of diffractive element and solar cell. Another aspect is the combination of a front side texture and a backside structure.

Additionally we present a method to consider the wave - optical effects provided by the diffractive structure in a simulation of the electrical properties of a solar cell.

Acknowledgements

The authors thank Elisabeth Schäffer, Juliane Klatt and all colleagues from Fraunhofer ISE who had a part in this work.

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