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ONE-DIMENSIONAL SIC PHOTONIC STRUCTURES TO ENHANCE THE EFFICIENCY OF SYSTEMS WITH SILICON SOLAR CELLS AND UPCONVERTERS

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ABSTRACT:
In silicon solar cells, photons with energies lower than the fixed bandgap of 1.12 eV are transmitted through the semiconductor material and do not contribute to current generation. This limitation can be overcome using an upconverting material below the solar cell, which transforms two or more low-energy photons into one high-energy photon, which can be utilized in the solar cell. Available efficient upconverters like $NaYF_4$:Er, however, typically only work efficiently over a narrow wavelength range. The used spectral range can be enlarged with a second luminescent material, which absorbs over a wider spectral range and emits in the absorption range of the upconverter, a concept known as spectral concentration. In this paper, we investigate photonic structures for a special system applying both spectral and spatial concentration using fluorescent concentrators. The photonic structures ensure that all photons reach the part of the system where they can be used the most efficiently. We show that the required photonic structures can be realized with a one-dimensional stack of alternating layers of silicon carbides with different silicon to carbon ratios. We present results of the simulation and optimization of these photonic structures, as well as characterization of such structures produced in a PECVD process.
Keywords: Photonic Structures, Silicon Carbide, Upconversion

1 INTRODUCTION

A semiconductor is transparent for photons with energies below the bandgap of the material. Therefore, photons in this range cannot contribute to the current generation in semiconductor solar cells and their energy is lost. For silicon-based solar cells, 20% of the incident solar energy are lost by this mechanism. Upconversion of low-energy photons presents a possibility to reduce these losses. Thereby, the theoretical efficiency limit of a silicon solar cell can be increased from close to 30% [1] up to 40.2% [2].
Available upconverting materials, like $NaYF_4$ doped with Er^{3+}, however, only show low upconversion efficiencies. As upconversion is a non-linear process [3], the conversion efficiency can be increased by concentrating light onto the upconverter. Furthermore, typical upconverter materials only work efficiently over a narrow wavelength range. The spectral range used for upconversion can be extended, however, with a second luminescent material, which absorbs over a wider spectral range and emits in the absorption range of the upconverter [4], a concept known as spectral concentration. This paper is based on a special concept, developed by Goldschmidt et al [5], which uses both spatial concentration, and spectral concentration with fluorescent concentrators, to increase upconversion efficiency. The concept is visualized in Figure 1.

In order to operate efficiently, it is crucial that all photons are distributed according to their energies and reach the part of the system where they are utilized most efficiently. For example, all photons in the range where the upconverter works efficiently should reach the upconverter pads. This is achieved using spectrally selective photonic structures. These structures ensure that photons with different energies are guided to the different parts of the systems.

In this paper we present an investigation of optimized one-dimensional photonic structures based on amorphous silicon carbide for this application. In Section 2, the required characteristics of the photonic structures are deduced. In Section 3, it is shown how the one-dimensional photonic structures are simulated using the transfer matrix approach. These simulated filters are subsequently improved for high reflection and transmission in the respective ranges, using an evolutionary algorithm.

The adapted filter structures are then prepared based on layered structures of amorphous silicon carbides with different silicon to carbon ratios which are prepared by PECVD (plasma enhanced chemical vapor deposition). The experimental results are presented in Section 4.

2 DESIRED CHARACTERISTICS OF THE PHOTONIC STRUCTURES

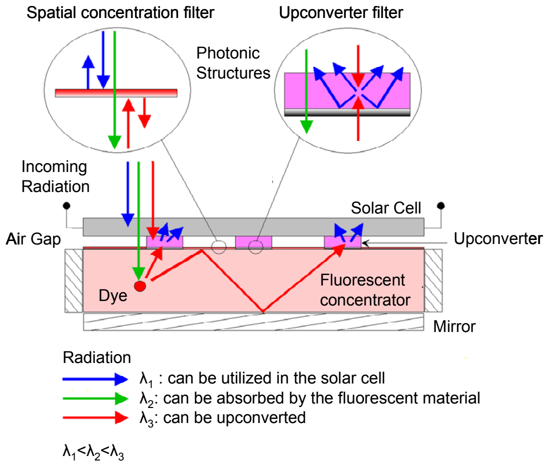

Figure 1: An advanced upconversion system. By the use of a luminescent material, a larger spectral range can be upconverted. Additional spatial concentration, further increases the upconverter efficiency due to its non-linear characteristics. [6]

The presented work is based on Er^{3+}- ions in a $NaYF_4$ host lattice as upconverting material. This material converts two low-energy photons at a wavelength of around 1523 nm to a photon with higher energy (at a wavelength of 800 nm to 980 nm). The solar cell is made from silicon. In Figure 1, light with energies above the bandgap of silicon is visualized as a blue arrow. These photons can be used directly to generate electron-hole-pairs in the solar cell. Hence they have to be guided from the upconverter into the solar cell and prevented from penetrating the fluorescent concentrator.

This requirement results in a spectrally selective filter structure needed below the upconverter, denoted as upconverter filter. This structure reflects all photons with wavelengths below 1100 nm. These photons can be used to generate electron hole pairs in the silicon solar cell. Additionally to the requested high reflection below 1100 nm, a high transmission above this wavelength region is required. This ensures that lower-energy photons are able to reach the fluorescent concentrator or the upconverter, depending on their energy. This filter structure is marked by a grey line in Figure 1 below the upconverter pads shown in purple. The filter characteristics of the upconverter filter are visualized in the inset shown on the right in Figure 1 and shown in Figure 2.

In principle, the same structure is needed below the solar cell, as for thin cells the low absorption coefficient of the indirect semiconductor silicon leads to the transmission of photons that could, in principle, be used for current generation. In conventional solar cells this is prevented by adding a mirror below the cell. In this system we want to use the transmitted part of the spectrum, hence, spectrally selective photonic structures are used. The structure reflects photons in the absorption range of silicon back into the cell. Additionally, this second filter structure situated between the solar cell and the fluorescent concentrator, has to prevent photons which can be efficiently used by the upconverter (marked by the red arrows) to escape the fluorescent concentrator. These photons have to be trapped in the fluorescent concentrator until they reach one of the upconverter pads. This filter is called spatial concentration filter.

This filter structure can be realized using a combination of two filters where the first one shows high reflection below 1100 nm and the second reflects above 1500 nm. In between, high transmission has to be realized. This allows the photons marked with a green arrow, which cannot be used directly in the silicon solar cell and are energetically above the upconversion region, to reach the fluorescent concentrator. For $NaYF_4$:Er^{3+}, the upconverting material used here, this upconversion region corresponds to wavelengths around 1530 nm. Thus, high energetic photons are reflected back into the solar cell and photons in the upconversion range are guided to the upconverter pads (see inset on the left in Figure 1) and Figure 3.

These requirements lead to two different filter designs needed to efficiently produce this system:

- the upconverter filter, which is present below the upconverter and reflects photons with wavlengths below 1100 nm and
- the spatial concentration filter, which has to show the same characteristics as the upconverter filter for the high-energy photons and additionally show high reflection for the spectrally concentrated light.

3 SIMULATION OF THE PHOTONIC STRUCTURES

The two different filter structures, described in Section 2 are produced in a one-dimensional configuration based on amorphous silicon carbide. This material is suitable as it has a larger bandgap than silicon and, therefore, shows no absorption in the wavelength range which is of interest here (wavelengths above 800 nm). Photons with higher energies are absorbed within the solar cell before impinging on the filter. The refractive index of amorphous silicon carbides can be tuned with the silicon to carbon ratio. Alternating layers of two configurations of silicon carbides with refractive indices of 1.9 and 2.6 at 633 nm are taken as a base for the simulations.

The simulation uses the transfer matrix approach. This approach includes the assumption of perfectly flat and infinitely extended layers and relates the electric and magnetic fields at the different boundaries [7]. In consequence, the transmission and reflection characteristics depending on the wavelength and incident angle can be determined.

As described above, the filter structures should have defined regions of high transmission and reflection. A simple filter that shows a high reflection peak as desired for the upconversion filter is the Bragg-filter.

Bragg-filters consist of alternating layers of two different materials with a high contrast of the refractive indices and with thicknesses corresponding to a quarter of the design wavelength. They can be designed to have very high reflection in the respective regions simply by increasing the number of bi-layers, but they typically show a large number of oscillations in the transmission region (see broken line in figure 2). Additionally, the width of the peak is fixed, depending on the design wavelength.

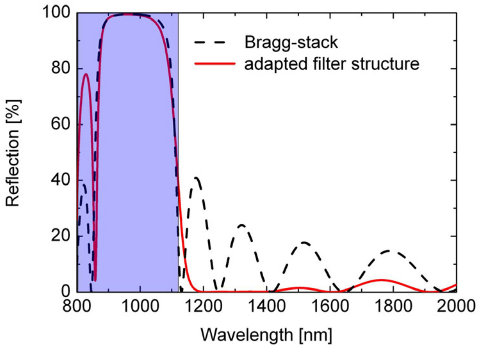

Figure 2: Simulations of the upconverter filter: the broken line shows a simulation of a Bragg-filter consisting of ten bi-layers showing a high reflection peak in the region where this is desired, but also a number of oscillations resulting in a reflection of up to 40% in the transmission region. The red line depicts the simulation of the adapted filter structure. The region of high reflection is highlighted in blue while high transmission is required otherwise.

To realize the solar cell concept in an efficient way, high transmission is required above the reflection region; therefore, edge filters have been designed. They are based on Bragg filters but are additionally optimized. Starting from the Bragg configurations, the thicknesses of the different layers are subsequently changed in order to improve the transmission and reflection characteristics in the respective regions. This optimization was performed, using an evolutionary algorithm.

The optimized edge-filter structure and a corresponding Bragg-stack are shown in Figure 2. Both structures consist of 20 alternating layers with refractive indices of 1.9 and 2.6 at a wavelength of 633 nm with thicknesses of 110 nm and 130 nm for the Bragg stack and thicknesses ranging from 30 nm to 200 nm for the adapted filter structure.

For the simulations, the filters are considered to be surrounded by material of a refractive index of 1.5 on both sides as this structure is required to be present at the boundary between the upconverter pads and the fluorescent concentrator, which are both embedded in a material of refractive index 1.5.

The same procedure can be used to simulate the spatial concentration filter. This filter is situated below the silicon solar cell in regions, where no upconverter is present. It has to ensure that light in the range where the upconverter works most efficiently reaches the upconverter pads.

This photonic structure needs to have a region of high transmission in between of two regions of high reflection. The transmission region is required to have a width of 400 nm, therefore, the filter characteristics is produced by the combination of the upconverter filter described above and a second filter having its reflection peak around 1700 nm. Both filters are required to have a high transmission in the other regions. The simulation procedure was carried out such that both filters have been optimized separately and subsequently combined introducing a λ/2 buffer layer. As a final step, this combined structure is optimized once again using the same algorithm considering both reflection regions and the transmission region in between.

This spatial concentration filter is simulated against air on the one side and silicon on the other side, thus, it can be deposited directly onto the silicon solar cell in the regions where no upconverter is located.

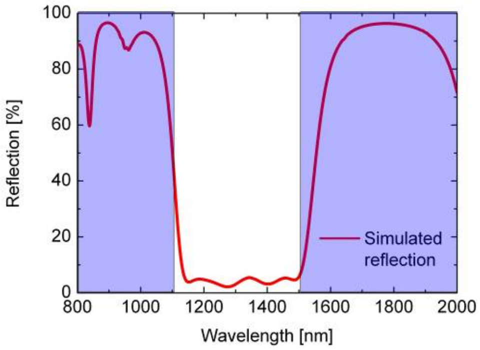

Figure 3: Spatial concentration filter showing high reflection below 1100 nm and above 1500 nm and high transmission in between. The filter was simulated against silicon and air as surrounding materials. The regions of high reflection are highlighted in blue while high transmission is required otherwise.

4 PHOTONIC STRUCTURES PRODUCED IN A PECVD-PROCESS

The refractive index of amorphous silicon carbide can be tuned with the carbon content [8]. In principle, the refractive index can vary from amorphous carbon to amorphous silicon. For the current application, thin and flat layers are required. Amorphous silicon carbides with higher silicon content grow faster and tend towards an island-like growth mechanism [9], thus, no thin layers could be obtained covering the whole sample surface. Therefore, the compositions are restricted and the maximum refractive index used here is 2.6 corresponding to a silane to methane gas flow ratio of one.

The simulated layers are deposited in a PECVD process in an AK-400 reactor built by Roth and Rau. As described above, layers with two different silicon to carbon ratios and, hence, two different refractive indices were used to simulate the filter structures and only the thicknesses of the layers have been changed to improve the filter characteristics.

In order to produce these two different configurations of amorphous silicon carbide, the deposition parameters like substrate temperature, microwave power and radiofrequency-power (rf) were kept constant and only the gas flow rates for methane and silane were changed. For the low-index layer, the gas flows were 110 sccm (standard cubic centimeters per minute) methane and 7 sccm silane and for the high-index layer 50 sccm methane and 50 sccm silane. The argon plasma is powered by two 1 kW microwave generators and an additional rf-generator operating at 13.56 MHz. Additionally, the plasma is diluted by 30 sccm hydrogen, which leads to a more homogenous deposition.

The filters were deposited as alternating layers with defined thicknesses onto a glass substrate. In order to determine the thicknesses and the dispersion characteristics of the different layers, they were characterized using a Woolam M-2000 spectroscopic ellipsometer. The measured values for refractive indices and layer thicknesses have been used to adapt the simulations of the filter characteristics with the method described earlier.

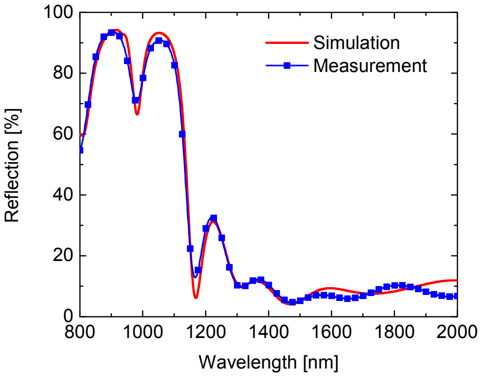

Figure 4: Upconverter filter produced with 20 layers of amorphous silicon carbide deposited on a glass substrate. The red line represents the simulated characteristics and the blue line shows the measurement. The thicknesses of the layers have been determined by spectroscopic ellipsometry and were taken as a base for the simulations.

The reflection characteristics of the produced filter structures were measured in a Cary500i spectrophotometer. The simulated reflection characteristics corrected for the layer thicknesses and the measurements show very good agreement. The most critical parameter in this respect is the thicknesses of the layers which should be deposited to a very high precision to the simulated values. With the processes used here, this was possible to a precision of roughly ±10 nm. Hence, the measured peaks typically show a lower peak reflectance and broader peaks compared to the simulations for the intended filter structure.

Figure 4 shows the comparison of measured and simulated reflection characteristics of the upconverter filter deposited on a glass substrate. The peak lies at the intended 1000 nm and above this wavelength, the reflection decreases to very low values. Figure 5 shows an SEM micrograph of the same filter.

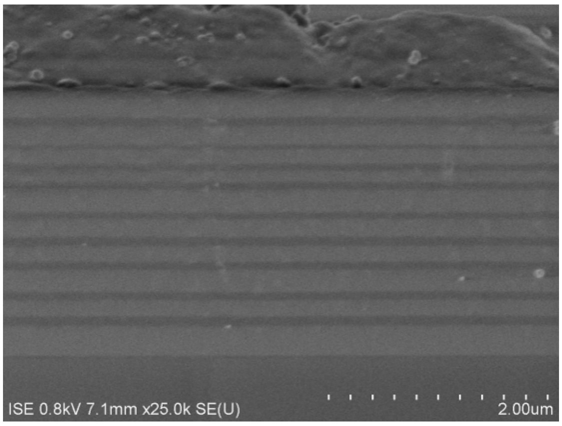

Figure 5: SEM micrograph of the polished cross-section of the upconverter filter with the characteristics shown in figure 4. The micrograph shows alternating a-Si_xC_{1-x}-layers of two different configurations with different thicknesses deposited on a glass substrate.

Furthermore, the spatial concentration filter needed above the fluorescent concentrator in the regions where no upconverter is present has been produced. The structure was realized based on the same material system, as stacked layers of silicon carbides with two different configurations. The measured reflection characteristic of this spatial concentration filter structure is shown in Figure 6.

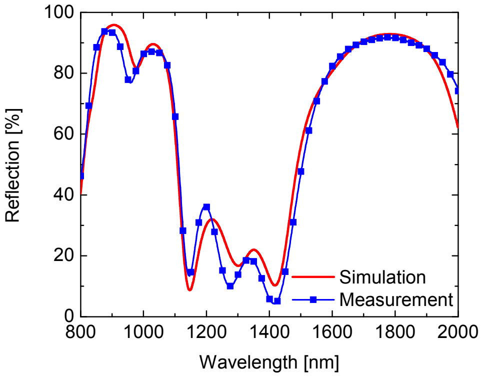

Figure 6: Comparison between the simulation and measurement of the spatial concentration filter. The structure consists in total of 35 layers of amorphous silicon carbide deposited on a glass substrate.

5 CONCLUSION

It has been shown that the photonic structures needed to produce an efficient solar cell system including upconverters and fluorescent concentrators, can be produced based on stacked layers of amorphous silicon carbides of different configurations.

The only disadvantage of this one-dimensional filter-setup is the angular dependence which cannot be completely circumvented. The evolutionary algorithm, applied to all possible angles improves the angular dependence by changing the layer thicknesses accordingly and hence reducing the symmetry, but still the high-reflection peak slightly shifts towards shorter wavelengths for larger incident angles. Three-dimensional photonic structures would show a different angular dependence which might be advantageous for this application.

It has been shown that the simulations and measurements of these one-dimensional photonic structures show very good agreement.

In spite of their angular dependence, producing these photonic structures in a layered structure based on the material system of silicon carbides is very promising.

6 ACKNOWLEDGEMENTS

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