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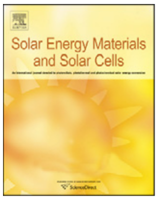

Theoretical short-circuit current density for different geometries and organizations of silicon nanowires in solar cells

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ABSTRACT

Radial junction solar cells are providing promising advantages of efficient light trapping and high built-in field when compared to their thin films or wafer based counter parts. In this work, we model short-circuit current densities for a wide range of nanowire arrays in order to define their optimal configurations. The modeling focuses on the fundamental nanowire properties, such as the nanowire length and the diameter, but also on their organization and on their density. The short-circuit current density is evaluated using rigorous coupled-waves analysis and normalizing the spectral absorptance by the standard AM 1.5 G solar spectrum. Results show that the nanowire density and length have the major impact on the device performance, while the nanowire organization is less important. Efficient light trapping properties of individual nanowires play an important role in the device performance and they have been further exploited in double-diameter nanowire arrays. An introduction of two different nanowire diameters into the same structure allowed for a separated optimization in two different spectral regions. As a result, we are reporting 10% increase in the short-circuit current density when double-diameter nanowire arrays were used.

1. Introduction

Recent boom in the solar cell industry has been caused primarily by the sufficient maturity of existing technologies and financial support of government entities promoting the renewable energy. In order to keep up with the growing energy consumption and to close the gap between prices of solar and fossil or nuclear energy, more innovations and technological advances are needed. Today's largest research efforts in the photovoltaic field are oriented towards maximizing the energy conversion efficiency while avoiding the inappropriate increase of the cost and thus reducing the price of the solar energy per kilowatt hour.

Thin film technologies provide an interesting alternative to the dominant silicon wafer based solar cells as they lead to more economical use of the silicon materials [1]. The major achievements for the amorphous silicon solar cells are represented by 10.1% overall efficiency [2], while tandem cells allows for as high as 11.9% efficiency [2]. Reported energy conversion efficiencies for triple junction thin film solar cells can be as high as 16.3% [3]. Further increase of the efficiency of a thin film based solar cell can be achieved by structuring the active region.

Very promising nanostructures for solar cells are silicon nanowires for their structural properties and possibility to make them in a crystalline silicon form. Nanowire based devices have high light trapping efficiency either due to efficient absorption of confined modes propagating through the vertical nanowires [4] or due to an enhanced scattering in the pseudo-random nanowire forests [5]. Both concepts represent material efficient solutions for enhanced light trapping required for a high performance photovoltaic device.

An economically viable approach for the nanostructured solar cells is the fabrication of silicon nanowires, either ordered in arrays or completely disordered. There are different methods to manufacture nanowires, e.g. by chemical etching into the crystalline silicon substrate [6] or vapor liquid solid method on different substrates including zinc oxide on glass or crystalline silicon [7–9]. Some of them allow for a more economical production (randomly oriented nanowires), while others can potentially overcome Yablonovitch limit [10] (vertically oriented nanowires).

The efficient light trapping inside nanowires has a very important application in the radial junction photovoltaic devices. Radial junction solar cells combine two important innovations to traditional solar cell designs: First, the active material itself is nanostructured and, second, the electrical field between p- and n-doped silicon is much stronger due to reduced distance between them. As a result, radial junction solar cells are not limited by the reduced carrier diffusion length, which is a typical problem for non-crystalline forms of silicon, e.g. amorphous phase silicon

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(thickness limited to 300 nm) or micro-crystalline silicon (often limited to 2 μm). The thickness of the intrinsic layer in p-i-n or n-i-p radial junction can be rather small (less than 100 nm [11,7]), while still allowing for a long nanowire length and excellent light trapping properties. This innovative approach opens the door for a new generation of solar cells with a nanostructured active layer as well as engineered build-in electromagnetic field intensity [12]. As it will be shown in Section 3, the efficient light trapping behavior of vertical nanowires is based mainly on the propagation of the light in the form of confined modes inside individual nanowires. This has an important implication of a relatively high tolerance of the manufacturing processes to the geometrical dimensions and nanowire organizations which is beneficial for the fabrication of nanowire based devices. Finally, this tolerance opens possibilities for less perfect (in the sense of periodicity), but also less expensive, fabrication of the nanowire based solar cells.

In the next section we introduce theoretical background for absorptance and short-circuit current calculations. Effects of structural parameters on light trapping effects inside vertical nanowire arrays are shown in Section 3, where the absorption inside vertical silicon nanowires under normal incidence is governed by an efficient light confinement. Theoretical short-circuit current calculated using AM 1.5 G spectrum is shown for different nanowires lengths, diameters and pitches. Dependence of the short-circuit current on the diameter and the pitch is shown for multiple nanowires lengths in the form of maps, for each nanowire organization separately. Maximal values of the short-circuit current are plotted as a function of the length showing nonlinear increase and comparable values between square and hexagonal nanowire arrays. Section 3 finishes with the introduction of a double-diameter nanowire structure allowing for further improvement of the device performance. The results are shortly concluded in Section 4.

2. Theory

In our work, vertical crystalline silicon nanowires are arranged into two-dimensional grids with supporting silver substrate as shown in Fig. 1. The incoming light is considered as a linearly polarized planar wave of a selected wavelength that approaches the structure at normal incidence. In the model, a silver substrate bellow nanowire arrays was used in order to avoid a situation where significant portion of the light is transmitted through the nanowire layer. A mirror or a highly reflective structure is always present at the bottom of the solar cell for increasing of the light absorption and current. The goal of the study will be to compare different configurations of nanowire diameters, densities, lengths and organizations and to show preferred combinations of these parameters for the optimal performance.

The optical response of silicon nanowires organized in a periodic arrays was modeled using 3D rigorous coupled-waves analysis (RCWA) [13,14]. The method is based on Fourier series expansions of a periodic electromagnetic field inside the structure with boundary conditions connecting tangential field components at interfaces between layers. The convergence of the method has been improved using inverse rules [15] and the scattering matrix approach for deeper structures (longer nanowires) [16].

The distribution of electromagnetic field was calculated in order to demonstrate efficient light trapping properties of silicon nanowire arrays. In this work we show either vertical cross-section through the middle of the nanowire or horizontal plane at the specified nanowire height. From the obtained electromagnetic field, the Poynting vector has been calculated as

$$\mathbf{P} = \Re(\mathbf{E} \times \mathbf{H}), \tag{1}$$

where **E** and **H** are vectors of the electric and the magnetic field, respectively. The symbol $\Re$ denotes the real part of a complex function or a number. For a clear illustration of energy losses during the wave propagation, the normal component of Poynting vector was calculated as follows:

$$P_z = \Re(E_x H_y - E_y H_x), \tag{2}$$

where E_x, E_y, H_x, and H_y denote the tangential components of the electric and magnetic field, respectively.

The RCWA does not provide the electromagnetic field distribution directly, as for instance finite-difference time-domain (FDTD) method [17] or finite elements method (FEM) [18] do, but the field can be reconstructed from the complete scattering matrix of the structure together with eigenvalues and eigenvectors inside each layer. The spatial distribution of the electromagnetic field is calculated as a sum of Fourier series expansion of all eigen modes,

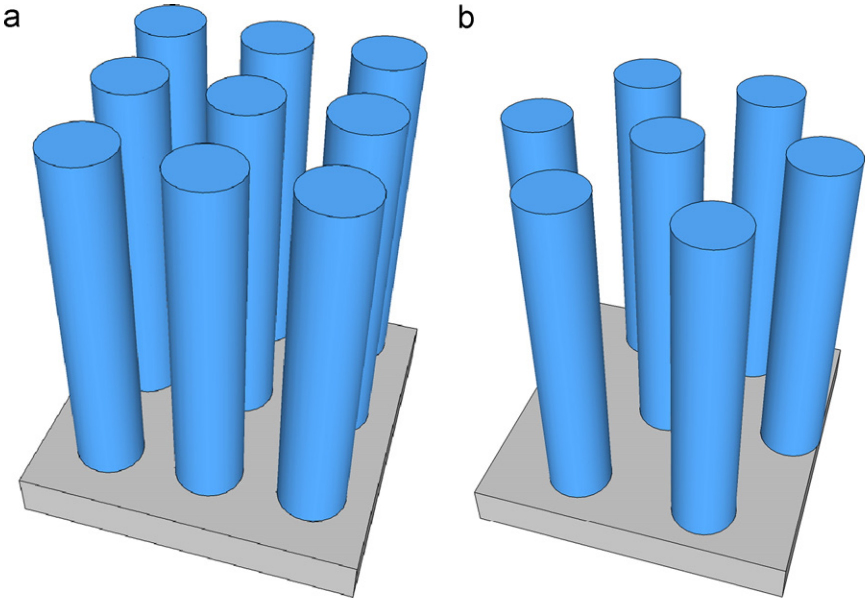

Fig. 1. Two different configurations of nanowire arrays on a silver mirror. Nanowires are organized either in (a) square periodic grid or (b) densely packed hexagonal periodic grid.

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