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Improved absorption efficiency of silicon (Si) solar cells through Resonant Waveguide Gratings (RWGs) – A hybrid design of RWG and Si solar cell

Muhammad Sohaib Badar [a], Muhammad Rizwan Saleem [a,b,*]

[a] National University of Sciences and Technology (NUST), U.S.-Pakistan Center for Advanced Studies in Energy [USPCAS-E (USAID Grantee)], Sector H-12, 44000, Islamabad, Pakistan
[b] Institute of Photonics, University of Eastern Finland, Joensuu, FI-80101, Finland

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ABSTRACT

This research work focuses on the improved performance of a Si solar cell by increasing solar absorption. The silicon solar cell is designed with a hybrid photonic structure of Resonant Waveguide Gratings (RWGs) to enhance absorption efficiency. The Waveguide Gratings have been designed in Fourier Model Method (FMM) using regression algorithm. The subsequent hybrid design of RWG with Si solar cell has been carried out using Finite Difference Time Domain (FDTD) design tool. The grating corrugated layer is designed in a fused silica (SiO_2) material and coated with a high index amorphous TiO_2 material. One of the possible realizable grating designed parameters are: grating period $d = 316$ nm, refractive index of TiO_2, $n_t = 2.385$, refractive index of fused silica $n_s = 1.450$, duty cycle = 65%, structure line width $w = 205$ nm, resonance wavelength $\lambda_r = 632.8$ nm (Helium-Neon laser), angle of incidence $\theta_i = 18°$, and grating grooved height $h_g = 120$ nm, whereas the designed parameters for Si solar cell are: refractive index of Si $N = 3.882 + i(0.019)$ at resonance wavelength $\lambda_r = 632.8$ nm, cell thickness $T = 500$nm. The employment of optimized grating parameters in simulations leads to efficient hybrid device performance.

1. Introduction

Solar cell technology is gaining interest as the most effective renewable energy technology to convert sunlight into electrical energy [1]. There are various forms of solar cells, for example, wafer-based silicon, thin-film silicon and multi-junctions solar cells [2–4]. Such categorization of solar cells depends on the fabrication processes and required materials one aims for [5]. It has been found that the energy conversion efficiency of a solar cell strongly depends on the absorption coefficient of the light within the material [6]. The absorption coefficient can be increased using efficient light-trapping techniques to improve the performance of a solar cell [7]. The light coming from the sun can be easily confined within the cell by designing proper photonic nanostructures, which will reduce the losses of reflection and scattering of light on the surface of the cell [8].

* Corresponding author at: National University of Sciences and Technology (NUST), U.S.-Pakistan Center for Advanced Studies in Energy [USPCAS-E (USAID Grantee)], Sector H-12, 44000, Islamabad, Pakistan.
E-mail address: rizwan.saleem@uef.fi (M.R. Saleem).

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The Resonant Waveguide Grating (RWG) is a Waveguide Grating Structure which enhances the resonant field and elongates the propagation path for light within the cell material. The grating layer, which is a phase matching element, brings the incoming light into multiple resonances in the device, eventually increasing the probability of light absorption due to enhancement in propagation length. The RWG consists of a single high index dielectric layer on a periodically corrugated transparent substrate to couple light. RWG effects of such photonic nanostructures are described on fused silica (SiO_2) grating to enhance light absorption. RWG structures are narrow band optical filters and have attracted much attention in the past two decades [9,10]. The periodic binary grating structures allow input light to couple with a collection of waveguide modes in the waveguide layer, resonate in the cell and ultimately confine light in the active region of the cell [11].

Employing such waveguide resonant properties, concentration of light elongates the interaction path for low energy photons to harvest [12]. Owing to the corrugated profile of the grating structure, the generated waveguide modes are leaky with complex propagation constant [12]. The incident light wave couples with these leaky waveguide modes and a resonance occurs when the incident wave and a leaky waveguide mode both are in same phase (i.e., phase matching) at particular incident wavelength, angle, and the geometrical parameters of the grating [13].

In this paper we report on design of a binary grating structure on fused silica (SiO_2) with an over-coated layer of amorphous titanium dioxide (TiO_2) as a waveguide layer. The design is carried out using Fourier Modal Method (FMM) on layered-structure [14]. Amorphous titanium dioxide (TiO_2) material is selected as a waveguide layer due to high refractive index, high dielectric constant, high transmittance in visible and infrared regions of solar spectrum, and low scattering losses [15]. Such effective and attractable properties of TiO_2 material make it a strong candidate in nanophotonic devices together with solar cell for efficient light confinement [16].

This paper comprises of two parts, in the first part we describe design of the RWG structure by using Fourier Model Method (FMM), while in the second part the TiO_2 coated SiO_2 grating structure is combined with silicon solar cell to design a RWG enabled Si solar cell. Such hybrid structure has been designed in the Finite Difference Time Domain (FDTD) software.

2. Resonant Waveguide Gratings (RWGs)

RWGs are very sensitive to polarization state of incident light that is TE (Transverse Electric) or TM (Transverse Magnetic) [17]. When plane light waves are incident on the grating structure, the incoming light wave couples with the waveguide mode by diffraction on the grating and resonance occurs; the resonance wavelength depends on the phase matching element of the grating layer [12]. The effective mode propagation constant β for the evanescent diffracted wave at the phase matching condition is given by [18].

$$\beta = k_0 \left(n_a \sin\theta_i - i\frac{\lambda}{d} \right) \tag{1}$$

where $k_0 = 2\pi/\lambda$ is the wave vector, λ is the wavelength of light in vacuum, n_a is refractive index of air, θ_i is the incident angle and d is the grating period. At resonance, the reflected and transmitted waves consist of two coherent components: the direct reflection/transmission, called the Fresnel reflection/transmission from the corrugated profile and the diffracted coupled wave of the grating [19]. An interference occurs by the combination of these two waves that depends on the phase difference between two waves in the vicinity of the resonance regime (phase can be varied from 0 to π) [19]. If the interfering waves have same phase then there will be no transmission and all the energy will confine in reflection and this phenomenon gives a 100% reflectance peak at a specific wavelength of incident light wave, which is called as resonance wavelength [18,10]. The resonance wavelength depends on the grating parameters i.e., grating period, grating grooved height, structural linewidth and the refractive indices of materials and surroundings [20].

In this research work, we study the increase in light absorption in silicon solar cells by applying RWG concept. The RWG grating structure is basically a phase matching element which enables the incident light to undergo multiple resonances to enhance the probability of light confinement within the material [13,20], whereas, a simple solar cell cannot absorb sunlight such as in RWG structure. In a planar structure most of the light is reflected and scattered from the surface of solar cell, which is eventually a loss in the efficiency of cell [21]. While RWG structure reduces the scattering and reflecting loss of light by providing interfaces to the incoming light to propagate and confine within the cell material [22]. This enhancement in light confinement by RWG structure increases the efficiency of the solar cell by increasing its optical absorption [11]. For an efficient light confinement, the RWG structure may be designed in such a way to support multiple resonances in all regions of the solar spectrum. This can be achieved by designing the grating structure having grating period less than the wavelengths of incident light [13,20].

2.1. Design and simulation of RWG

The schematic representation of the RWG structure is shown in Fig. 1. The design parameters considered for one-dimensional RWG are: grating period d = 316 nm, refractive index of TiO_2 film n_t = 2.385, thickness of TiO_2 layer t = 50 nm, refractive index of fused silica (SiO_2) substrate n_s = 1.450, refractive index of the air n_a = 1.00, duty cycle = 65%, structural line width w = 205 nm, resonance wavelength λ_r = 632.80 nm, angle of incidence $\theta_i = 18^\circ$, and grating grooved height h_g = 120 nm. The grating shown in Fig. 1 is illuminated by a TE-polarized plane wave. The design of sub-wavelength ($d < \lambda$) grating structure is accomplished after optimizing appropriate engineering parameters to yield 100% reflectance efficiency for TE-polarized