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Original article

Impact of distributed Bragg's reflectors and nanogratings in thin film silicon solar cells

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ABSTRACT Photonic crystals possess periodic modulation of higher refractive index contrast which brings a unique photonic band gap. In this work, thin-film silicon solar cell optical performance was studied by the finite-difference time-domain (FDTD) method. The distributed Bragg reflector (DBR) and nanogratings are integrated as a backside reflector, which endorses the photonic modes in the silicon solar cell. The light trapping scheme plays a pivotal role in solar cells due to the limited absorption in the higher spectral region. For that, various silicon solar cell structures are investigated for better light absorption using photonic ray theories with numerical simulations. This result indicates the combination of DBR and nanogratings is capable and yielded a high relative enhancement of 59 % as compared with the reference cell which was endorsing the Fabry–Perot resonance and guided-modes in photovoltaic devices. These results show promise for designing thin film silicon solar cells with enhanced light absorption.

KEYWORDS DBR, nanogratings, silicon, thin-film, FDTD

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1. Introduction

Photonic crystals are attractive due to the unique optical performance in photovoltaic devices that convert optical power into electricity. As one-dimensional (1D) photonic crystals also known as distributed Bragg's reflector (DBRs), which is responsible for the desired optical reflectance from the shorter (300 – 700 nm) and longer spectral (> 700 nm) region by tuning different optical parameters such as refractive index contrast between the selected materials, incidence wavelength, angle of wavelength, thickness of the each layer etc [1]. The low-cost, easy fabrication and large scale manufacturing are the key factors, which are focused on by researchers. For that, thin-film crystalline silicon solar cells are the best candidate for future energy needs. In solar cells, one of the major challenges is the achievement of higher light absorption from thin film. In the photovoltaic (PV) market, the efficiency of thin film solar cells is very low due to their weak absorption in the longer (infrared) spectral region. Because of the light-trapping effects, thin film silicon solar cells have become a vital route to improve solar cell conversion efficiency. For that, the light trapping mechanism might be improved by various nanostructures integrated into thin-film solar cells such as nanoparticles (nanospheres), nanogratings, distributed Bragg reflectors, nanopillars, nanopyramids, nanodisks etc. [2–4]. The thin film solar cells are theoretically (simulation) studied by various methods, such as rigorous-coupled wave analysis (RCWA), finite-difference time-domain method (FDTD) and finite element method (FEM) [5, 6]. To date, light trapping mechanisms have been employed by incorporating various dielectric/metallic nanostructures including various shapes of nanostructures like nanoparticles and nanogratings [7–9]. This light trapping mechanism helps one to improve their omni-directional scattering and reflection. In the reported work, one describes different types of nanogratings used in thin film solar cells, such as triangular gratings [10], rectangular gratings [11], square gratings [12], dual gratings [13], double gratings, etc [14]. Tahmineh investigated the impact of one-dimensional photonic crystals as back reflectors on thin-film crystalline silicon (c-Si) solar cells using the two-dimensional (2D) FEM method. The obtained results showed an improved current density by integration of DBR (24.01 mA/cm^2) and nanogratings (24.51 mA/cm^2) in thin film c-Si solar cells [15]. Sanshui et al. demonstrated crystalline silicon (c-Si) solar cell performance by integrating the front and back-side of the metallic gratings. They have achieved the highest current density enhancement factor of 1.9 within a 200 nm thick c-Si absorber layer [16]. Dubey et al. studied the performance of SiO_2/Si_3N_4 multilayers and nanogratings for better amorphous silicon (a-Si) solar cell devices by using chemical vapor deposition and RCWA methods. With the effect of dielectric multilayers and nanogratings, 79 % relative enhancement was achieved as compared to the reference solar cell [17]. Saravanan and Dubey investigated the influence of 1D photonic (SiO_2) and plasmonic (Ag) nanostructure for the improvement of amorphous silicon solar cells using the RCWA method. The light harvesting enhanced in shorter and longer spectral regions and achieved the maximum current density of 33.54 mA/cm^2 [18]. Chen et al. experimentally prepared thin film amorphous silicon (a-Si) solar cells with a backside reflector of 6 pairs of ZnO/a-Si distributed Bragg reflectors using a magnetron sputtering method. The fabricated 6 DBR pairs achieved a reflectance of 99 % and the stop-band (photonic band) from 686 to 1354 nm. They demonstrated the 50 % absorption enhancement noticed in the visible and near-infrared spectral region [19]. Heidarzadeh et al. presented the improved light trapping analysis in thin film silicon solar cells using RCWA, FEM and FDTD methods. They used rectangular and triangular gratings in the absorber region and the solar spectral range from 400 to 1100 nm. Under transverse electric (TE) polarization mode, the highest cell efficiencies of 20, 22.1 and 23.53 % were achieved with 2.5, 5 and 7.5 μm thick silicon solar cells [6]. The major goal of this work is reducing the cost (naturally abundant silicon) and improving the light absorption in thin-film silicon solar cells by integrating photonic nanostructures, which are easy to fabricate at device level.

In this paper, we focus on the optical performance of thin-film crystalline silicon solar cells using the finite-difference time-domain method. The designing parameters and simulation methods are discussed in Section 2. In Section 3, the optical properties (absorption, quantum efficiency) of the simulated solar cell are discussed. Finally, we conclude the work in Section 4.

2. Designing approach

Figure 1 shows the schematic diagram of a thin-film silicon solar cell with the integration of Si_3N_4-anti-reflection coatings (ARCs) and back reflector of SiO_2 nanogratings and distributed Bragg's reflector (DBRs, a-Si/SiO_2). The numerical investigation was carried out using the FDTD method (RSoft), which is useful to solve the issue between the matter (solid) and electromagnetic waves. The proposed solar cell anti-reflection coating (ARC) layer is made of silicon nitrate (Si_3N_4) with a thickness of 70 nm. Next, DBR or one-dimensional photonic crystals consist of five alternative layers (stacks) such as amorphous Si (a-Si) and silicon-di-oxide (SiO_2) thin films. The corresponding DBR refractive indices (n_i) are 3.6 ($n_{\text{a-Si}}$) and 1.45 (n_{SiO2}), respectively, and the center wavelength (λ_C) for light is 800 nm. The thickness of each DBR layer is determined by the quarter-wave principle ($t = \lambda C/4n$), where, n is the refractive index of the material, so we get the thickness of a-Si ($t_{\text{a-Si}}$) and SiO_2 (t_{SiO2}) are 56 and 138 nm. The crystalline silicon ($t_{\text{Si}} = 1.5\ \mu$m) acts as an absorber (intrinsically flat) and the photonic structures like periodic grating (or) photonic crystals should be directly imprinted on the c-Si layer. On top of the DBR (or bottom of the absorber), we further implement the integration of one-dimensional dielectric grating with a period ($G_p = 0.6\ \mu$m). The SiO_2 nanogratings have a duty cycle (G_{dc}) of 0.5 and a thickness of 0.1 μm. The alternative periodic SiO_2 grating structure was embedded in between the c-Si layer and the DBR. It guides and enhances the light scattering and diffraction of light into the PV device. The total thickness of the thin film silicon solar cell is 2.54 μm.

The complete electric field distributions are simulated and investigated using the finite-difference time-domain method. It has periodic boundary conditions (PBC) on the X-axis to avoid boundary issues and a perfect matched layer (PML) applied on Y and Z-axis [5]. The PML is also known as the absorbing layer and is useful for absorbing (without any

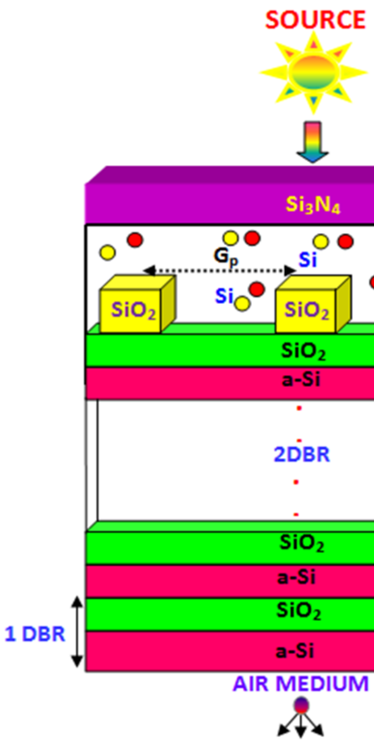

FIG. 1. The schematic diagram of the thin film silicon solar cell

reflection between the interfaces) the incident light that is travelling outward from the bounded domain [8,20]. This entire simulation process is carried out using RSoft synopsis tools. The incident spectrum is considered from the range of 300 to 1200 nm (λ) and beyond that the photons are unabsorbed.

3. Results and discussion

We have simulated thin film silicon solar cells using the FDTD method. This method is useful to solve the transverse electro (TE)/magnetic (TM) problems in Fourier space through Maxwell's equations.

3.1. Quantum efficiency

The quantum efficiency and light absorption spectra of different solar cell structures are measured and compared in Figs. 2 and 3. First, the quantum efficiency of various thin film solar cells is shown in Fig. 2. To get a clear understanding and the role or influence of backside reflector structures in solar cells, they are named as, 1) reference (ARC+Tc), 2) ARC+Tc+DBR, 3) ARC+Tc+GRA+DBR and 4) ARC+Tc+GRA+Metal BR. Here, 'Tc' is active (absorber) layer, 'ARC' is antireflection coatings, 'DBR' is distributed Bragg reflector (or one-dimensional photonic crystals) and 'Metal BR' is the aluminum metal back reflectors. Further, the incident light or photon energies are converted as charge carriers which are collected by the solar cell device. The quantum efficiency is the function of wavelength from 300 to 1200 nm. For instance, the conversion and collection of the carriers are enhanced (red dotted) with the assistance of back reflector of DBRs and nanogratings generated and increased quantum efficiency in the ultraviolet and infrared region. Tsai et al. reported that the DBRs integrated solar cells proved higher external quantum efficiency in the ultraviolet and visible spectral regions [19,21]. The quantum efficiency for the thin film silicon solar cell showed reducing in the near-infrared spectral region with the effect of recombination losses. The metal back reflector (ARC+Tc+GRA+Metal BR) showed the increased performance (green solid line). Next, the reference cell (ARC+Tc) generates less collection of the carriers (blue solid lines).

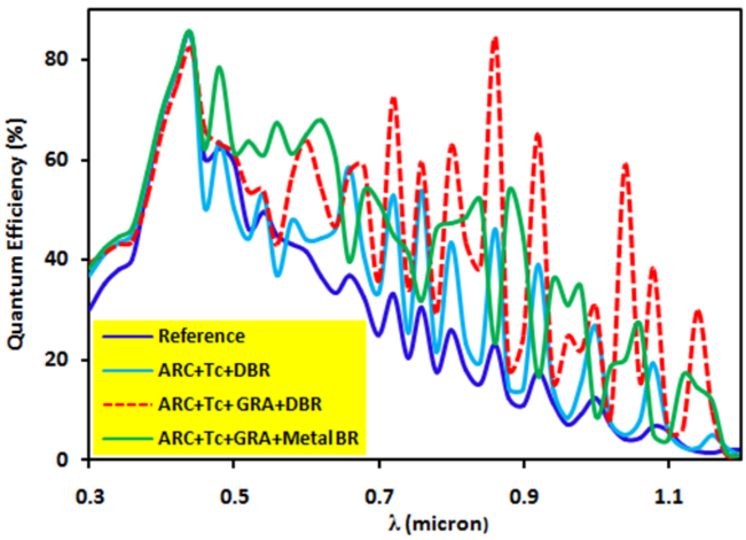

FIG. 2. The quantum efficiency as a function of wavelength (μm)

3.2. Absorption

The light absorption of different thin-film silicon solar cells is shown in Fig. 3 which demonstrates the influence of dielectric nanostructures of DBR and gratings in the silicon solar cell. The dielectric SiO_2 nanogratings help to extend the photon path length (or life time) in the silicon absorber region by maximizing the diffraction and larger scattering angle. However, the highest light absorption is achieved by 'ARC+Tc+GRA+Metal BR' structure in ultraviolet spectral region (green solid line). The diffraction of photons was calculated with the following equation:

$$n_x \sin\theta_m + n_y \sin\theta_i = \frac{N\lambda}{d}, \tag{1}$$

where, n_y is the refractive index of light incident material layer, n_x is the refractive index of the outgoing material layer, d is the constant, λ is the wavelength, N is the diffractive order ($N = 0, 1, -1, 2, -2$,...), θ_i the incident angle and θ_m is the diffractive angle [22,23].

Furthermore, we have compared different types of silicon solar cells and studied the improved light absorption. In particular, DBR with nanogratings showed the highest light absorption due to the significant light scattering with the assistance of SiO_2 nanogratings and unusual (highest) reflection from five stacks of Si/a-Si DBR layers. The absorption

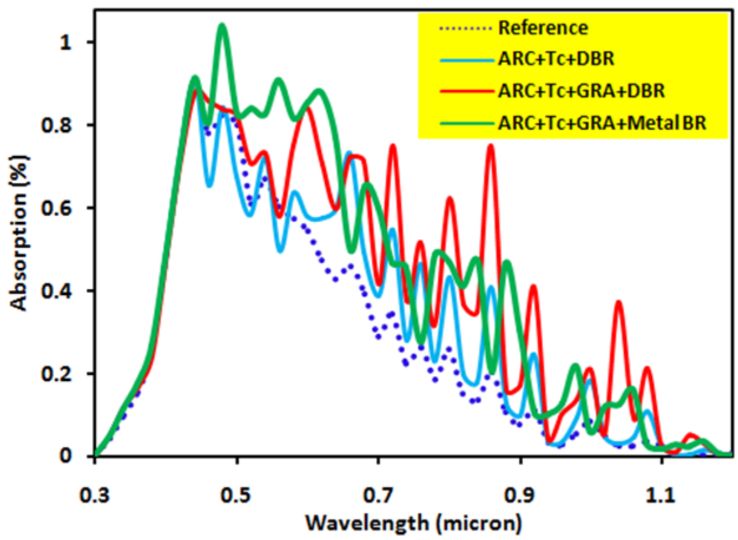

FIG. 3. The absorption (%) as a function of wavelength (λ) for various thin film silicon solar cell

result reached a value greater than 80 % and the highest absorption peaks were obtained for the spectral range from 450 to 1100 nm. In the silicon absorber region, the incident light absorption, $A(\lambda)$ can be calculated by the following equation:

$$A(\lambda) = 1 - R(\lambda) - T(\lambda). \tag{2}$$

Here, $R(\lambda)$ is the total reflection and $T(\lambda)$ is the total transmission from the proposed silicon solar cell. By placing monitors, the light reflectance (R) and transmittance (T) were calculated from the front surface and the rear surface (or backside) of the solar cell [11]. At longer spectral wavelengths, reduced optical performance is noticed, which is hampered by the various parameters like non-absorption of reduced photon energy, thermal losses from the absorption of high energy light photons, electrical losses, parasitic losses, extraction losses with the effect of unavoidable recombination losses from the charge-carriers etc [24]. This significant performance was achieved with the effect of Fabry–Perot resonance mode and surface guided modes (Fig. 4). With the addition of the distributed Bragg reflector (DBR) to the planar structure, the electric field evanescently decays into the DBR and it is reflected backwards (or) repetition in to the light path. The back reflector structures (or photonic crystals) are known as perfect mirrors (back reflecting). Since the light can be diffracted into oblique angles to enhance the absorption length. Compared to a smooth surface (reference cell) with the 'ARC+Tc+GRA+DBR' solar cell, the photon optical path length and lifetime increased as evidenced by their optical performance in Figs. 2 and 3. The solar cell power conversion was measured using numerically a sun simulator under AM1.5 conditions [20, 25].

The optical characteristics are changing with respect to the back reflectors or with the level of the irradiance (incidence) spectrum. In this section, the Maxwell's equation is solved and the electric field distribution in the proposed silicon solar cell structure is at 860 nm (λ_C). Under the normal solar incident spectrum, the boundary conditions were applied for the achievement of TE field distribution. The transverse electric, TE (E_y) field is shown in Fig. 5 with an incidence wavelength (λ_C) of 860 nm. The incident light is reflected at each layer interface. The incident light (L_I) at a certain wavelength propagates into the DBR layers by considering a few factors (units) such as reflected light (L_R) and light (L_I) obtained from the interfaces. The electric field distribution shows a strong light trapping mechanism due to the Fabry–Perot resonance and surface guided modes (white region in the active region) [26–28]. The irradiating light is partially reflecting and diffracting into the 1.5 μm thick silicon active layer region and transmitting into the air. The diffraction from the bottom nanogratings constructively interferes with the absorber region. This higher absorption originates from the periodic diffraction gratings and DBR layers. The transverse electric field is highly confined in the absorber region. Further, the intensity bar confirmed the strong field (cyan and blue colors) noticed in the final cell structure due to the DBR plus periodically arranged nanogratings [6]. The open circuit voltage ($V_{OC} = 0.7$ A/m^2) and fill factor ($FF = 84.5$ %) were noticed.

3.3. Current density

The dielectric back reflectors show a significant performance in thin film silicon solar cells as evidenced by Figs. 4 and 6 and by calculation of the current density (J_{SC}, mA/cm^2) and relative enhancement (%). In Fig. 4, we summarize and compare the optical performance of various thin film silicon solar cells by changing the various backside reflectors or back reflector. The J–V relationship for the solar cell is calculated and it is dependent on the absorption of light photons under normal incidence angle (0°) and the AM1.5G spectrum. This photo-generated current (J_{SC}) is directly related to the collection of the photon absorption of the silicon absorber [12].

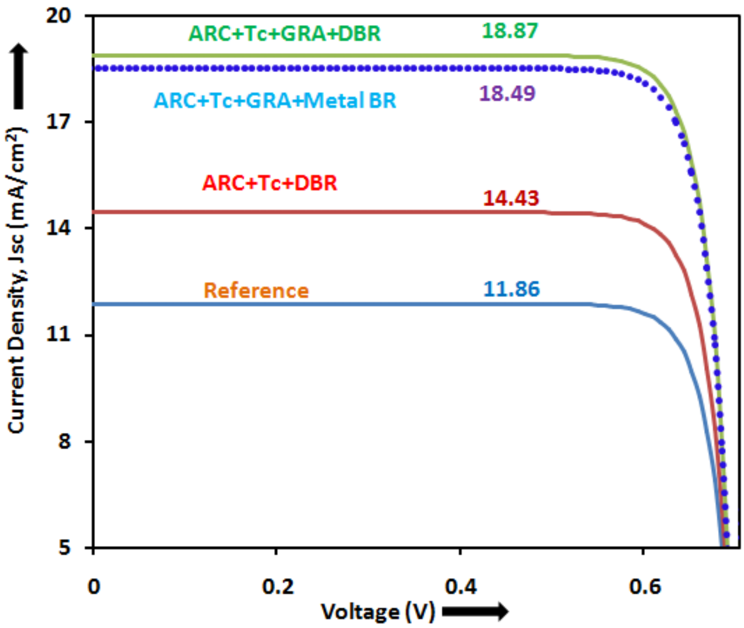

FIG. 4. The types of current density vs voltage

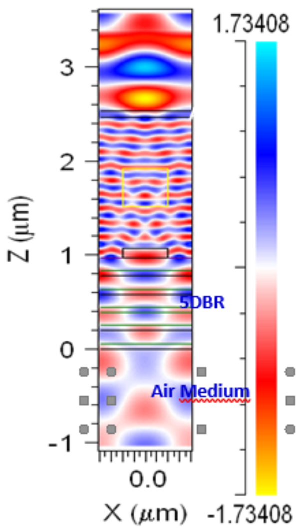

FIG. 5. The electric field (E_y, 860 nm) distribution of silicon thin film solar cell

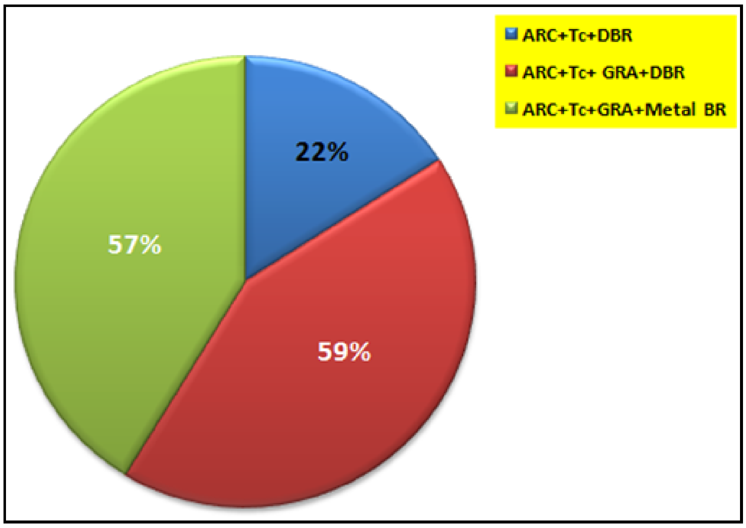

FIG. 6. The relative enhancement of various silicon solar cells

With the advantage of light trapping, the highest current density is received by absorbing the number of photons in the absorber region. The current density (J_{SC}) was calculated by using the following equation as,

$$J_{SC} = \frac{e}{hc} \int_{300}^{1200} \lambda A(\lambda) \frac{dI}{d\lambda} d\lambda, \tag{3}$$

where, e is the electron, h is the Planck's constant, c is the speed of light, λ is the wavelength, I is the incident solar spectrum, and A is the absorption [18]. The light trapping mechanism significantly improved and went back to the silicon absorber region. The DBR and nanogratings integrated cell '(ARC+Tc+GRA+DBR)' structures highly dominated for their improved current density compared to 18.87 mA/cm^2 as shown in Fig. 4. This optical performance is enhanced with the effect of photonic nanostructures. In the silicon absorber region, surface guided modes (white color) are noticed with the addition of effective photonic nanostructures including SiO_2 nanogratings and DBR layers. The metallic back reflector replaced by DBR showed improved current density as compared with the reference solar cell. Fig. 6 depicts the relative enhancement of various types of crystalline silicon thin film solar cell. The combination of periodic SiO_2 nanogratings with 5DBR showed improved performance as indicates 59 % enhancement as compared to the reference solar cell due to the photonic effects such as Fabry–Perot resonance, surface guided modes. The plasmonic silicon solar cell integrated with a 200 nm thick aluminum back reflector yielded improved performance up to 57 %.

Overall, photovoltaic performance highly improved with respect to semiconductor materials due to the photonic effects. The designed multilayer based solar cell could be fabricated by using various techniques such as sol-gel spin coatings, magnetron sputtering, dip-coatings, electrochemical etching and plasma enhanced chemical vapour deposition (PECVD) techniques [29, 30].

4. Conclusions

In conclusion, we have theoretically investigated the light trapping mechanism of different thin film crystalline silicon solar cells by using FDTD numerical analysis. The combination of photonic nanostructures is capable for improving the current density due to their higher refractive index ratio. The DBR (a-Si/SiO_2) and nanogratings (SiO_2) were integrated as a backside reflector in a thin-film silicon solar cell and yielded the highest light absorption in the visible and near infrared region. The different solar cells are investigated in terms of quantum efficiency, absorption, and current density. Further, we have calculated the relative enhancement up to 59 % as compared to the reference cell due to the photonic modes of Fabry–Perot resonance and guided modes. This enhanced light trapping mechanism within the nanoscale will be greatly evident because of the better absorption in solar cells. Furthermore, the photo-current will be enhanced by considering optimization of each parameter.

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Conflict of interest: the authors declare no conflict of interest.