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Design and analysis of multilayer waveguides containing nanoparticles for solar cells

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ABSTRACT

A novel waveguide structure containing nanoparticles with various substrate media has been proposed to find out the transmission and reflections of the incident light on the proposed structure. The Transfer matrix method has been applied to study the transverse electric TE and the transverse magnetic TM waves at an Antireflection (AR) coating structure for silicon solar cells with a nanoparticles-dielectric layer. The transmission and reflection coefficients have been derived at different incident angles of light and for various substrate's materials in wavelength region between 300 nm and 1200 nm. The numerical results, obtained by MAPLE software, highlight an enhancement of the transmission coefficient and reduction of the reflections for different substrate media.

1. Introduction

In recent decades, a remarkable and growing interest has been devoted to solar photo-voltaic technology (Matheu et al., 2008; Jonsson et al., 2011; Shabat and Ubeid, 2014; Mousa and Shabat, 2015; Pillai and Green, 2010; Park and Lee, 1998; Nagel et al., 1999) due to the expected lack of the conventional resources of the energy and environmental concerns. Solar energy represents a clean energy source with high availability and simple implementation potential. However, to become more competitive to established sources of energy, a need for higher efficiency of the solar cells arises, which leads to the construction of new solar cell design based on the concept of the waveguides and on novel antireflection coatings structures. While antireflection coatings (AR) for the visible and the infrared regions have also long attracted much research and development due to their simple design and technological implementation, nanoparticles technology has just recently been used to enhance thin film solar cells (Matheu et al., 2008; Jonsson et al., 2011). For instance, it is possible to improve AR coatings by adding nanoparticles on the cover region, (Shabat and Ubeid, 2014; Park and Lee, 1998) leading to a minimization of the reflection and maximization of the transmission. Nanoparticles composed of silicon materials have been used in this structure due to its low cost, longterm stability, abundance in nature, and the existing established technology (Pillai and Green, 2010; Park and Lee, 1998; Nagel et al., 1999; Garnett and Yang, 2010; Green and Keevers, 1995; Berning, 1963; Schaadt et al., 2005).

The aim of this work was to design and analyze multilayer waveguide solar cell containing nanoparticles. The effects of the proposed waveguide structure on the reflected light are investigated in terms of the fraction of the nanoparticles, the thickness of the layer and the properties of the medium containing the nanoparticles.

2. Theory

We consider a regular array of spherical silicon nanoparticles arranged as schematically shown in Fig. 1. In this figure d_1 is the diameter of a silicon nanoparticle which equals to the thickness of the first layer and d_2 is the thickness of the second layer (SiN_x). The cover in our computation is chosen to be air, glass, and silicon, which are typical materials used in such designs. The Maxwell-Garnett effective medium approximation is used to calculate the effective permittivity of the composite materials formed by silicon nanoparticles (dielectric spheres) DS in the dielectric host, DH air and in SiN_x. The effective permittivity is then given by Ruppin (2000), Genzel and Martin (1973):

$$\varepsilon_{eff} = \varepsilon_b \frac{\varepsilon_i(1+2f) + 2\varepsilon_b(1-f)}{\varepsilon_i(1-f) + \varepsilon_b(2+f)} \quad (1)$$

where ε_b is the permittivity of the host (base) material, ε_i the permittivity of the nanoparticle's materials and f the volume fraction of the particle in the host medium.

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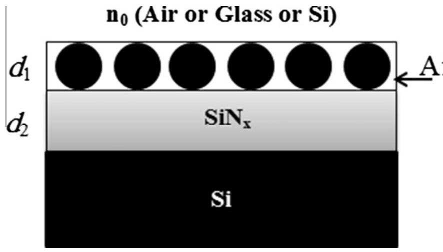

Fig. 1. Schematic diagram of the multilayer nanoparticles waveguide structure.

The volume fraction of the particles in the host medium can be obtained by expressing the volume of the nanoparticle layer to be $V_{layer} = L \times l \times d$, where d is a thickness of layer, L is the length of a silicon solar cell surface, and l is the width of a silicon solar cell surface. For simplicity, take $L = l = 1$ cm. The volume for spherical particle of radius r is: $V_p = 4\pi r^3/3$. The number of a particles on the layer can be assumed to be: $N_p = (L/p) \times (l/p)$ where p is the period of the two-dimensional array. Thus, the volume fraction of the particles in the nanoparticle layer is: $f = (N_p \times V_p)/V_{layer}$.

This effective permittivity will now be examined for the two limiting cases. First, when the volume fraction of the particles in the host medium is f = 1, the effective permittivity is $\varepsilon_{eff} = \varepsilon_i$, which means that the nanoparticles are occupying all the host medium. Second, when the volume fraction of the particles in the host medium is f = 0, the effective permittivity equals that of the base medium.

To demonstrate the performance of the proposed multilayer AR coatings, we consider light incident from air upon the composite medium of silicon hosted in the air region, and include all incident angles (0–90).

The method used for calculating the reflectance R of a system of thin films involves a matrix formulation of the boundary conditions at the film surfaces derived from Maxwell's equations (Katsidis and Siapkas, 2002; Troparevsky et al., 2010; Born and Wolf, 1975; El-Amassi et al., 2015). This method makes it possible to determine the reflectance R and transmission T of a system of thin films for obliquely incident, polarized light. For simplicity, a special case of normal incidence reflectance will be presented here.

The 2×2 transfer matrix that relates the field components at two successive boundaries is defined as follows (Katsidis and Siapkas, 2002; Troparevsky et al., 2010; Born and Wolf, 1975; El-Amassi et al., 2015):

$$M_k = \begin{bmatrix} \cos(\delta_k) & \frac{\mathrm{i}\sin(\delta_k)}{\gamma_k} \\ \mathrm{i}\ \gamma_k\ \sin(\delta_k) & \cos(\delta_k) \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} E_a \\ B_a \end{bmatrix} = M_k \begin{bmatrix} E_b \\ B_b \end{bmatrix} \tag{3}$$

where $\delta_k = 2\pi n_k d_k \cos(\theta_k)/\lambda$ is the phase difference, d_k its thickness, γ_k is the so-called optical admittance, and θ_k is the propagation angle following Snell's law ($n_0 \sin\theta_0 = n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3$).

In the case of the oblique incidence, the admittance values of TE and TM are different. For the number k layer, they are as follows:

$$\gamma_k = \begin{cases} n_k \cos\theta_k & \textit{for TE polarization} \\ n_k/\cos\theta_k & \textit{for TM polarization} \end{cases} \tag{4}$$

For m layers, overall transfer matrix (M_T) is defined in terms of individual matrix as follows:

$$M_T = M_1 M_2 M_3 \ldots M_m = \prod_{k=1}^{m} M_k = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{5}$$

The reflection coefficient and the reflectance can be calculated from the elements of the system of transfer matrix as follows (Schaadt et al., 2005; Ruppin, 2000; Genzel and Martin, 1973):

$$r = \frac{m_{21}}{m_{11}} \tag{6}$$

$$R = |r|^2 \tag{7}$$

The total reflectance R for the solar cell is defined as the average of both values R^{TE} and R^{TM}, and is written as follows:

$$R = \frac{R^{TE} + R^{TM}}{2} \tag{8}$$

3. Results and discussions

Using the outlined transfer matrix method above, the reflectance of light has been calculated for the proposed waveguide structure model using MAPLE software, taking into account the period p varies between 135 nm and 400 nm. In our computation, the usual operating wavelengths have been used which vary between 300 and 1200 nm (Jonsson et al., 2011; Shabat and Ubeid, 2014; Mousa and Shabat, 2015; Pillai and Green, 2010; Park and Lee, 1998; El-Amassi et al., 2015; Brendel, 2003; Saylan et al., 2015; Huihui et al., 2011; Simovski et al., 2013). This range is active region of solar radiation, while there is very little solar radiation left beyond this range. It is also worth mentioning that for Si technology, the infrared region is less important due to the gap of Si.

Fig. 2 displays the variation of the percentage of reflected light as a function of the wavelength of the incident light for different values of the volume fraction of the nanoparticles f in the host medium and the air cover medium. It shows that increasing the fraction of the nanoparticles leads to the lowest reflected percentage of the light, and the best particular of the observation occurs at f = 0.15 as the lowest reflected percentage has been observed through the visible light between 500 and 650 nm.

Fig. 3 illustrates the variation of the reflected percent of light with the operating wavelength of the light for different values f, and the glass cover medium. It also confirms the pervious observation of increasing the fraction f, leading to decreasing the reflected percent of the light. It has also been found that the increasing of the fraction f makes the gap between the curves getting very narrow as it has clearly been observed for the curves labeled

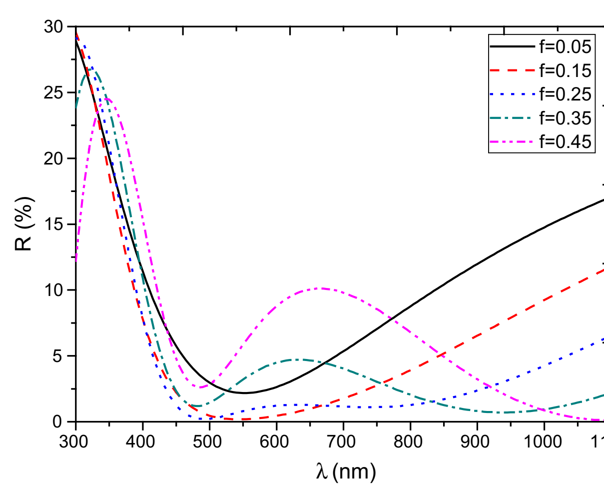

Fig. 2. The reflected percent of light of the proposed structure for different values of f and the air cover medium, and d_1 = 125 nm, d_2 = 60 nm, n_0 = 1, n_2 = 2.3, and n_{Si} = 3.5.

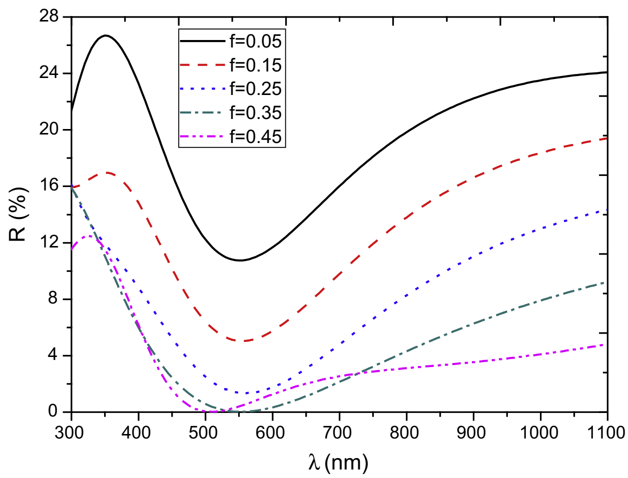

Fig. 3. The reflected percent of light of the proposed structure for different values of f and the glass cover medium, and d_1 = 125 nm, d_2 = 60 nm, n_0 = 1.47, n_2 = 2.3, and n_{Si} = 3.5.

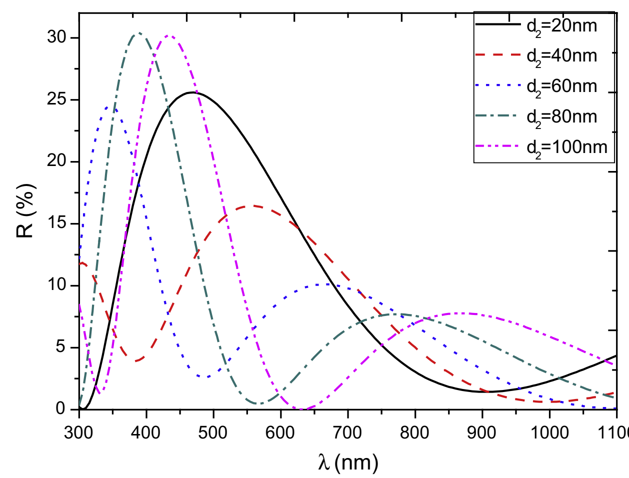

Fig. 5. The reflected percent of light of the proposed structure for different values of d_2 and the air cover medium, and d_1 = 125 nm, f = 0.45, n_0 = 1, n_2 = 2.3, and n_{Si} = 3.5.

f = 0.35 and f = 0.45. The very minimum or zero reflected light occurs twice at f = 0.35 and f = 0.45, and this is very interesting result, which could be taken into account in designing future solar cells.

Fig. 4 shows the reflected percent of light versus the operating wavelength of the light for different values f, and the silicon cover of the proposed structure. In this case the reflected light has higher values than the previous cases. It confirms the other results as the increasing f leads to the lowest reflected light. So Figs. 2–4 display that the minimum reflected percentage of the light has been observed for the cover medium for air, glass, and silicon respectively, showing that the decreasing the refraction index of the cover medium decreases the reflected light.

For Figs. 5–7 the minimum percent reflection of the light has been observed at the thickness d_2 = 60 nm confirming the concept that the minimum reflected light occurs at the thickness equal the quarter wavelength and also proving the high efficiency in the solar cells happened in the thick layer of the proposed solar cell as in reference Brendel, (2003).

Fig. 8 displays the reflected percent of light versus the operating wavelength for various values of the incident angle and the air cover of the proposal structure. The reflected spectra for various

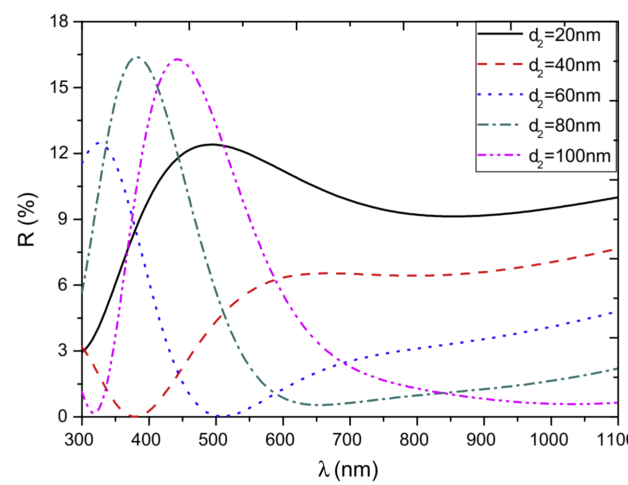

Fig. 6. The reflected percent of light of the proposed structure for different values of d_2 and the glass cover medium, and d_1 = 125 nm, f = 0.45, n_0 = 1.47, n_2 = 2.3, and n_{Si} = 3.5.

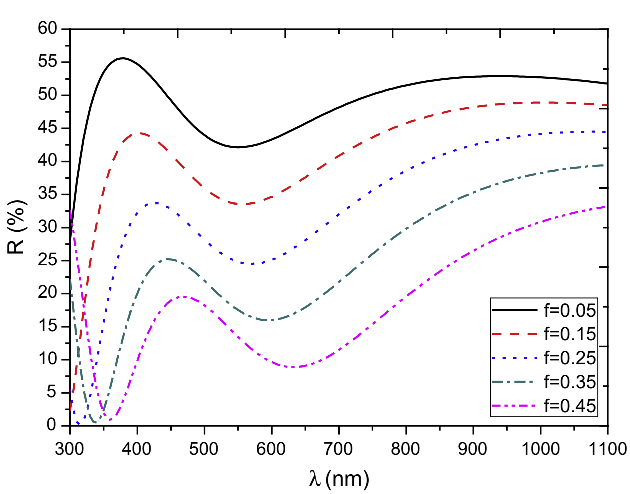

Fig. 4. The reflected percent of light of the proposed structure for different values of f and the silicon cover medium, and d_1 = 125 nm, d_2 = 60 nm, n_0 = 3.5, n_2 = 2.3, and n_{Si} = 3.5.

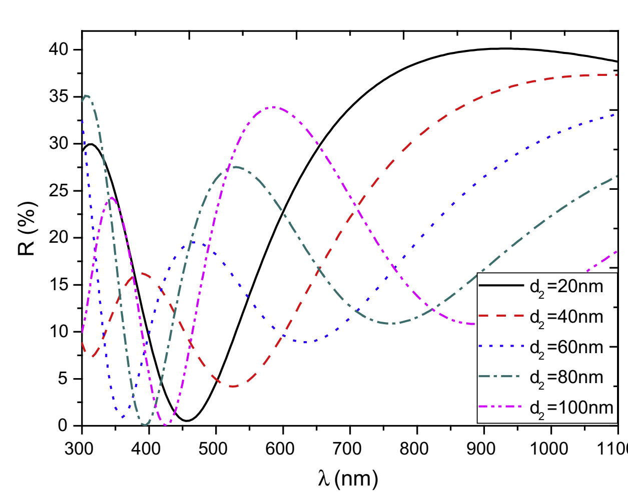

Fig. 7. The reflected percent of light of the proposed structure for different values of d_2 and the silicon cover medium, and d_1 = 125 nm, f = 0.45, n_0 = 3.5, n_2 = 2.3, and n_{Si} = 3.5.

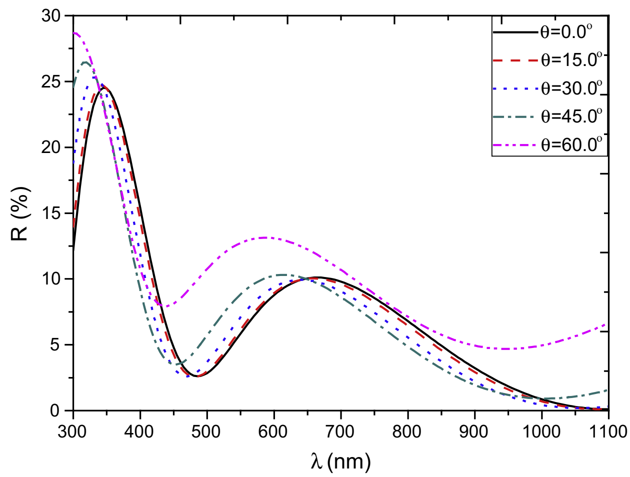

Fig. 8. The reflected percent of light of the proposed structure for different values of incidence angle and the air cover medium, and d_1 = 125 nm, d_2 = 60 nm, f = 0.45, n_0 = 3.5, n_2 = 2.3, and n_{Si} = 3.5.

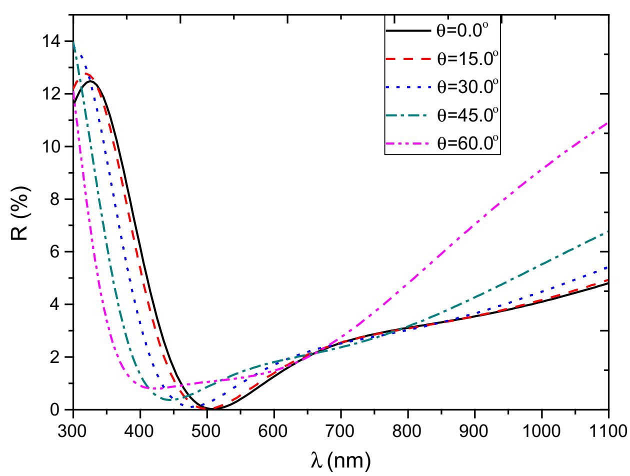

Fig. 9. The reflected percent of light of the proposed structure for different values of incidence angle and the air glass medium, and d_1 = 125 nm, d_2 = 60 nm, f = 0.45, n_0 = 3.5, n_2 = 2.3, and n_{Si} = 3.5.

values of the incident light are approaching zero for the incident angles less than 30° and at the wavelength are larger than 950 nm and the other minimum values are noticed between 420 and 550 nm.

Fig. 9 shows the reflected percent of light versus the operating wavelength for various values of the incident angle and the glass cover of the proposal structure. At certain wavelength values, the reflectance is minimized and can be tuned by matching the other physical parameter as the thickness and the incident angles.

From Figs. 8 and 9, in general, the minimum values of the reflected percent in the structure with glass cover are less than the structure with air cover. We have also noticed that the best result of having the minimum reflected percent appears at the zero incident of light.

In brief, we found that the glass cover in the waveguide structure is better in having the minimum reflected light and can easily be tuned with other physical parameters as the nanoparticles film, thickness, and the incident angle. We also realized that the nanoparticles fraction has more effects than other parameters as the incident angles.

We have found that the considered waveguide structure has better efficiency and less minima of the reflected percent of light than previous various waveguide structures (Schaadt et al., 2005; Saylan et al., 2015; Huihui et al., 2011; Simovski et al., 2013).

4. Conclusions

This study represents an easy to implement theoretical approach for optimizing new waveguide structures for solar cell containing nanoparticles within a cover medium on top of the basic solar cell structure. The used approach is based on both the Calausius-Mossotti for modeling the effective permittivity of the nanoparticles embedded in other media, and the transfer matrix method to find out the transmission and the reflection spectra of the proposed waveguide structures. It is clear that the nanoparticles can enhance the transmission and reduce or minimize the reflection which are very important in optimizing light management in future solar cells.

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