Efficiency Enhancement of Solar Cell Using Metamaterials

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Abstract

In this work, Photovoltaic (PV) cell model with high absorption efficiency is introduced. The proposed four layer PV cell model consists of antireflection coating (ARC) layer on glass based and covered by metamaterial (MTM) bounded by air. The effect of the refractive index of MTM as well as the effect of the incident angle on the reflectance are considered. Results showed that the reflectance of the PV can be controlled by changing the reflectance index of MTM as well changing the incident angle.

Keywords: Antireflection coating (ARC); Metamaterials; Solar Cell; Optimization; Reflectance; PV efficiency.

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Introduction

Renewable energy known as environmentally friendly attracted a lot of attention due to the energy crises especially in the third world. Solar energy is the most promising among other sources of renewable energy because of its abundance in nature and cleanness. The main component in the system is the PV cell. For a PV cell to work appropriately its absorption to sun light must be optimized. Different works have been establish to reach the optimal values for light absorption by PV cell with maintaining reasonable cost of the cell.

These studies focused in using antireflection coating (ARC) to improve the internal structure of the PV cell [1]. The simplest structure is achieved by using a single ARC on a substrate. Different materials are used for ARC as in [2-5]. SiN_x is the mostly used as ARC because it has high refractive index value

that can varied by changing deposition paramters [6]. A more complex PV cell that lead to mimimum reflecance at wider range of wavelengths is achieved by using double ARC with different materials. Examples of double layer ACR is found in [6-9]. Beye [10] proposed a double ARC solar cell with same materials of SiN_x.

In his work, the minimum reflectance is achieved below 5%. In this work, we poposed a solar cell waveguide structure model with even lower reflectance that reach as low as 1% using double layer one of them is ARC and the other is metamaterial (MTM). Metamaterial is a noval material fabracted at laboratory with negative refractive index. They assume different refractive index by changing certain parameter as in [11, 12]. Next section is dedicated to introuce the proposed PV cell. Section 3 presents the results and discusion. Finally, the conclusion is given in section 4.

Proposed Solar Cell (PV)

Figure 1 exhibits the structure of the proposed solar cell. In the structure, the PV cell consists of SiN_x thin film deposited on glass and covered by MTMs bounded by air. The refractive indices as denoted in Figure 1 are n_0, n_1, n_2, and n_s for air, MTMs, SiN_x and glass respectively. MTM layer thickness is d_1 while the film thickness is d_2. The light is assumed to shine on the PV at oblique incidence with different incidence angle (θ_0).

For oblique incidence, the optical admittance for the kth layer including negative index materials is derived in the paper of [13, 14] for both transverse electric field polarization (TE) and transvers magnetic field polarization (TM) as follows:

$$\gamma_k^{TE} = \frac{1}{\eta_0 \mu_k} n_k \cos\theta_k \qquad \text{-------(1)}$$

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$$\gamma_k^{TM} = \frac{1}{\eta_0 \mu_k} \frac{n_k}{\cos\theta_k} \quad \text{-------(2)}$$

Where θ_k is related to θ_0 by Snell's law

$$n_0 \sin\theta_0 = n_k \sin\theta_k \quad ;k = 1,2,...m \quad \text{-----(3)}$$

The 2x2 transfer matrix that relates the field components at two successive boundaries (e.g. a and b) is defined as follows:

$$M_k = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos(\delta_k) & \dfrac{i\sin(\delta_k)}{\gamma_k} \\ i\gamma_k \sin(\delta_k) & \cos(\delta_k) \end{bmatrix} \quad \text{---(4)}$$

$$\begin{bmatrix} E_a \\ B_a \end{bmatrix} = M_k \begin{bmatrix} E_b \\ B_b \end{bmatrix} \quad \text{-----(5)}$$

where $\delta_k = 2\pi n_k d_k \theta_k / \lambda$ is the phase difference. For m layers, the overall transfer matrix (M_T) is defined in terms of individual matrix as follows:

$$M_T = M_1 M_2 \ldots M_m = \prod_{k=1}^{m} M_k \quad \text{----(6)}$$

Then the reflectance can be derived from equation (5) and (6). The reflectance $R = |r|^2$ where r is the reflection coefficient defined as:

$$r = \frac{E_{r1}}{E_0} \quad \text{----(7)}$$

Following [13, 14], the reflectance for our system is derived for both TE and TM polarization as follows.

For TE the reflectance R^{TE} is

$$R^{TE} = \frac{\begin{array}{l} n_0^2 \cos^2(\theta_0)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_2\cos(\theta_2)}{n_1\cos(\theta_1)}\sin(\delta_1)\sin(\delta_2)\right]^2 \\ + \left[n_0\cos(\theta_0)n_s\cos(\theta_s)\right]^2\left[\frac{\cos(\delta_1)\sin(\delta_2)}{n_2\cos(\theta_2)} + \frac{\sin(\delta_1)\cos(\delta_2)}{n_1\cos(\theta_1)}\right]^2 \\ + \left[n_1\cos(\theta_1)\sin(\delta_1)\cos(\delta_2) + n_2\cos(\theta_2)\cos(\delta_1)\sin(\delta_2)\right]^2 \\ +n_s^2\cos^2(\theta_s)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_1\cos(\theta_1)}{n_2\cos(\theta_2)}\sin(\delta_1)\sin(\delta_2)\right]^2 - 2n_0\cos(\theta_0)n_s\cos(\theta_s) \end{array}}{\begin{array}{l} n_0^2\cos^2(\theta_0)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_2\cos(\theta_2)}{n_1\cos(\theta_1)}\sin(\delta_1)\sin(\delta_2)\right]^2 \\ + \left[n_0\cos(\theta_0)n_s\cos(\theta_s)\right]^2\left[\frac{\cos(\delta_1)\sin(\delta_2)}{n_2\cos(\theta_2)} + \frac{\sin(\delta_1)\cos(\delta_2)}{n_1\cos(\theta_1)}\right]^2 \\ + \left[n_1\cos(\theta_1)\sin(\delta_1)\cos(\delta_2) + n_2\cos(\theta_2)\cos(\delta_1)\sin(\delta_2)\right]^2 \\ +n_s^2\cos^2(\theta_s)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_1\cos(\theta_1)}{n_2\cos(\theta_2)}\sin(\delta_1)\sin(\delta_2)\right]^2 + 2n_0\cos(\theta_0)n_s\cos(\theta_s) \end{array}} \quad \text{--(8)}$$

and for TM the R^{TM} is

$$R^{TM} = \frac{\begin{array}{l} n_0^2\cos^2(\theta_0)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_2\cos(\theta_2)}{n_1\cos(\theta_1)}\sin(\delta_1)\sin(\delta_2)\right]^2 \\ + \left[n_0\cos(\theta_0)n_s\cos(\theta_s)\right]^2\left[\frac{\cos(\delta_2)\cos(\delta_1)\sin(\delta_2)}{n_2} + \frac{\cos(\theta_1)\sin(\delta_1)\cos(\delta_2)}{n_1}\right]^2 \\ + \left[\frac{n_1\sin(\delta_1)\cos(\delta_2)}{\cos(\theta_1)} + \frac{n_2\cos(\delta_1)\sin(\delta_2)}{\cos(\theta_2)}\right]^2 \\ +n_s^2\cos^2(\theta_s)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_1\cos(\theta_1)}{n_2\cos(\theta_2)}\sin(\delta_1)\sin(\delta_2)\right]^2 - 2n_0\cos(\theta_0)n_s\cos(\theta_s) \end{array}}{\begin{array}{l} n_0^2\cos^2(\theta_0)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_2\cos(\theta_2)}{n_1\cos(\theta_1)}\sin(\delta_1)\sin(\delta_2)\right]^2 \\ + \left[n_0\cos(\theta_0)n_s\cos(\theta_s)\right]^2\left[\frac{\cos(\delta_2)\cos(\delta_1)\sin(\delta_2)}{n_2} + \frac{\cos(\theta_1)\sin(\delta_1)\cos(\delta_2)}{n_1}\right]^2 \\ + \left[\frac{n_1\sin(\delta_1)\cos(\delta_2)}{\cos(\theta_1)} + \frac{n_2\cos(\delta_1)\sin(\delta_2)}{\cos(\theta_2)}\right]^2 \\ +n_s^2\cos^2(\theta_s)\left[\cos(\delta_1)\cos(\delta_2) - \frac{n_1\cos(\theta_2)}{n_2\cos(\theta_1)}\sin(\delta_1)\sin(\delta_2)\right]^2 + 2n_0\cos(\theta_0)n_s\cos(\theta_s) \end{array}} \quad \text{--(9)}$$

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

$$R = \frac{R^{TE} + R^{TM}}{2} \quad \text{----(10)}$$

The Total reflectance (equation (10)) is solved using the software Maple 13 to verify the characteristics of the proposed PV cell.
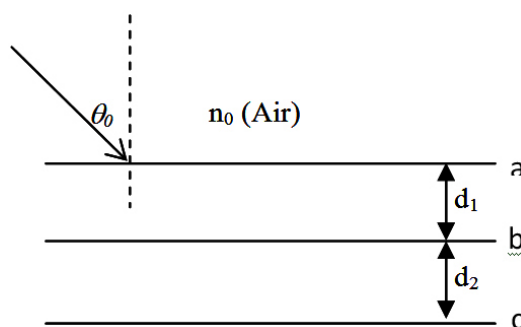
Results and Discussion

The structure under consideration has film consisting of SiN_x on glass substrate with n_s=1.47, and covered by negative refractive index MTM bonded from above by air with n_0=1. The thicknesses d_1 and d_2 are taken to be equal the quarter wavelength at each media ($d_m = \lambda_m/4$), where $\lambda_m = \lambda/n_m$ and n_m is the refractive index for each media. Usually the wavelength λ is chosen close to the peak of the solar spectrum (λ=600nm). The spectral response of SiN_x goes from 300-1200nm [10]. Thus, this range is taken to limit the spectrum of the incident light. In our calculation, we consider first normal incidence with n_1=-2 and vary n_2 to achieve optimal value of n_2 at which the reflectance equals zero. Figure 2 exhibits the total reflectance R as calculated from equation (10) using Maple 13. In the calculation, we let n_2 assume the following values: 2.5, 2.4, 2.3, and 2.2 as indicated in Figure 2. We notice that the spectral takes zero value when n_2=2.4 and all other curves maintain a reflectance lower than 1%. Comparing our result with one or two ARC layers in Beye calculations [10], we obtain a better result since his system maintained reflectance fewer than 5%.

To further check the optimal structure, we let n_2=2.4 and vary n_1 as in Figure 3. We realize that the optimal value of n_1=-2. Moreover, with excluding n_1=-1.6, we found that reflectance at 600 nm below 1.5% which lower than the values obtained by [10].

Figure 4 displays the results for the proposed PV cell at n_2=2.4 and n_1=-2 with oblique incidence. We notice that for low angles (θ_0=0°,15°,30° and 45°) the reflectance is below 4.5% almost in the whole spectrum and for θ_0=60° the reflectance is below 8% for the whole spectrum. These results are better than the result obtained by Beye [10].

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Figure 1. The schematic of the proposed nanostructure Solar Cell.

Figure 2. The reflectance calculated for n_1=-2, under normal incidence.
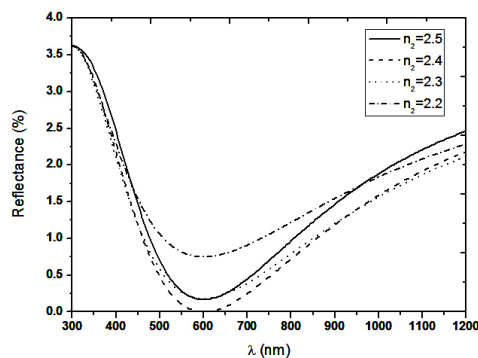
Figure 3. The reflectance for n_2=2 and under normal incidence.
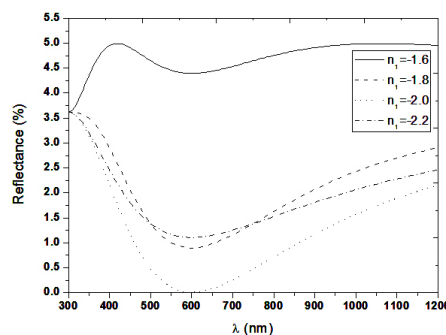
Figure 4. The reflectance for oblique incidence when n_1=-2 and n_2=2.4.
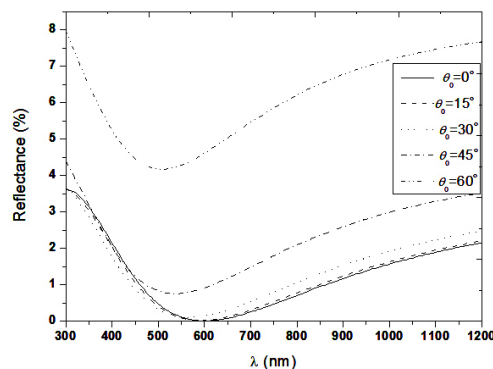
Conclusion

In this work, we proposed double layer PV cell with different materials where one layer consists of MTM and the other is ARC made of SiN_x. The double layers are bounded from below by glass and coved by air. The average reflectance is numerically solved using maple 13. The numerical calculations are obtained under different condition; by varying the MTM parameters, or varying SiN_x refractive index, or at different incident angles. Results show that the average reflectance reached its minimum when n_1=-2, n_2=2.4 and for normal incidence. Moreover, the average reflectance under different conditions low compared to other proposed structures. The results are useful to improve the efficiency of PV cell.

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