Dena M. El-Amassi, Hala J. El-Khozondar, Mohammed M. Shabat (2015) Efficiency Enhancement of Solar Cell Using Metamaterials.

Research Article

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 cleanliness. 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 established 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]. SiNx is the mostly used as ARC because it has high refractive index value that can vary by changing deposition parameters [6]. A more complex PV cell that lead to minimum reflectance at wider range of wavelengths is achieved by using double ARC with different materials. Examples of double layer ACR are found in [6-9]. Beye [10] proposed a double ARC solar cell with same materials of SiNx.

In this work, we proposed 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 novel material fabricated at laboratory with negative refractive index. They assume different refractive index by changing certain parameters as in [11, 12]. Next section is dedicated to introduce the proposed PV cell. Section 3 presents the results and discussion. 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 SiNx thin film deposited on glass and covered by metamaterial (MTM) bounded by air.

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 transverse magnetic field polarization (TM) as follows:

\[
\gamma_k^{TE} = \frac{1}{\eta_0 \mu_k} n_k \cos \theta_k
\]

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

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.

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

\[
M_k = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos(\delta_k) & i\gamma_k \sin(\delta_k) \\ i\gamma_k \sin(\delta_k) & \cos(\delta_k) \end{bmatrix} \tag{4}
\]

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

\[
M_T = M_{m-1}M_{m-2} \ldots M_2M_1 = \prod_{k=1}^{m} M_k \tag{6}
\]

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

\[
r = \frac{E_{t1}}{E_0} \tag{7}
\]

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

\[
R_{TE} = \frac{R^2 + R_{TM}^2}{2}
\]

and for TM the \(R_{TM}\) is

\[
R_{TM} = \frac{R^2 + R_{TE}^2}{2}
\]

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

\[
R = \frac{R_{TE} + R_{TM}}{2} \tag{10}
\]

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 \(n_1=1.47\), and covered by negative refractive index MTM bonded from above by air with \(n_2=1\). The thicknesses \(d_1\) and \(d_2\) are taken to be equal the quarter wavelength at each media \((d_i=\lambda_{s}/4)\), where \(\lambda_{s} = \lambda/n_s\) is the refractive index for each media. Usually the wavelength \(\lambda\) is chosen close to the peak of the solar spectrum (\(\lambda=600nm\)). 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 \(n_2=2.4\) 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 \(n_i\) 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 \(n_i=2.4\) and vary \(n_2\) as in Figure 3. We realize that the optimal value of \(n_2\) is where \(R\) is the smallest reflectance fewer than 5%. Moreover, with excluding \(n_2=1.6\), 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 \(n_2=2\) with oblique incidence. We notice that for low angles \((\theta=0^{\circ}, 15^{\circ}, 30^{\circ}, 45^{\circ})\) the reflectance is below 4.5% almost in the whole spectrum and for \(\theta=60^{\circ}\) the reflectance is below 8% for the whole spectrum. These results are better than the result obtained by Beye [10].
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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