THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 24, Number 3/2023, pp. 231–236
DOI: 10.59277/PRA-SER.A.24.3.04

SIMULATION OF LEFT-HANDED MATERIALS FOR GaAs SOLAR CELLS

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Abstract. The optical performance of photovoltaic solar cells and modules is affected by the significant reflection losses at the air/glass front interface. Several antireflection coating materials on solar glass are introduced to overcome this drawback as a mechanism for light trapping. We propose in this study a novel structure containing silicon nitride (SiN_x), left-handed materials (LHMs), and the light absorbing material (gallium arsenide, GaAs), to minimize the reflection and increase the light absorption. The transfer matrix method was used to compute the reflectivity and absorption of both normal and transverse magnetic polarized light. The results show that left-handed materials have an available good impact on the efficiency of solar cells by increasing the light absorption through the proposed structure where the absorbance achieves values greater than 80% in the entire light spectrum.

***Key words**:* solar cells, GaAs, left-handed materials, absorption, transfer matrix method, ARC.

1. INTRODUCTION

Metamaterials or left-handed materials (LHMs) are artificial effectively homogeneous electromagnetic structures, where their electromagnetic properties differ qualitatively from the conventional materials, dielectric or metal. LHMs became well-known because of the negativity of both their permittivity (ε) and permeability (μ) that gives the antiparallel orientation of the wave vector ($\boldsymbol{k}$) and the Pointing vector ($\boldsymbol{S}$). LHMs were historically introduced theoretically by Veselago [1] when he analyzed the propagation of plane waves in materials having negative permittivity and permeability. Pendry et al. [2] suggested the artificial periodic wire, where the negative permittivity appears, and then the split-rings model leads to the negative permeability [3]. In 2000, Smith et al. [4, 5] constructed LHMs using the combination of split rings and periodic wires. They prepared several microwave experiments to investigate the properties of this new material. One year later, Shelby et al. [5] attained the first experimental investigation of the negative index of refraction on LHMs at microwave frequencies. Kong [6] studied the interaction of electromagnetic waves with stratified LHMs isotropic media. He studied the transmission and reflection waves, field solution of guided waves, and linear dipole antennas in the stratified structure of LHMs. Engheta [7] discussed some of the electromagnetic properties of LHMs, physics remarks, and probably future applications. Sabah et al. [8] used the transfer matrix method to determine the reflection and transmission powers due to the interaction of electromagnetic waves with a double slab of metamaterials. Chew [9] investigated the reflection on the LHM and the LHM energy conservation property. Cory and Zach [10] carried out the analysis of the reflection and transmission in multilayer structures containing metamaterials and dielectric slaps while others determine the propagation of light through metamaterials, including reflection and transmission estimations [11–16].

There is a vast amount of literature on the concept and practical realization of antireflection coating (ARC) for solar cells using single or multi-layered structures [17–24] to utilize solar energy more effectively. Different materials are used in the ARCs as LHMs which are deposited as a layer of it to enhance the absorption and decrease the reflection [25–31]. We have previously investigated ARCs consisting of glass/silicon nitride/LHM on a silicon substrate to enhance the absorption for silicon solar cells [26]. Nakayama et al. [32] used plasmonic nanoparticles to improve light absorption in GaAs solar cells. Bahrami et al. [33] studied the effects of ARCs on the performance of GaAs solar cells. Chen et al. presented to ARC using LHM for GaAs solar cells [34].

In this paper, we study the average absorption of double-layer antireflection coating (DLARC) containing SiN_x and LHM on top of a GaAs substrate. The transfer matrix method and Maple 13 program are used to compute the absorption of the proposed solar structure.

2. THEORY

The proposed structure consists of four layers as shown in Fig. 1, the first layer is air with $\varepsilon_0 = 1$ and $\mu_0 = 1$, and the second layer is SiN_x as a dielectric material with electric permittivity (ε_1) taking the values between 3.24 [18] where we assume its magnetic permeability $\mu_1 = 1$, the third layer is LHM with different electric permittivity (ε_2)and the magnetic permeability μ_2 is assumed to be -1 [31] and the substrate layer is GaAs substrate with $\varepsilon_s = 12.7$ and $\mu_s = 1$.

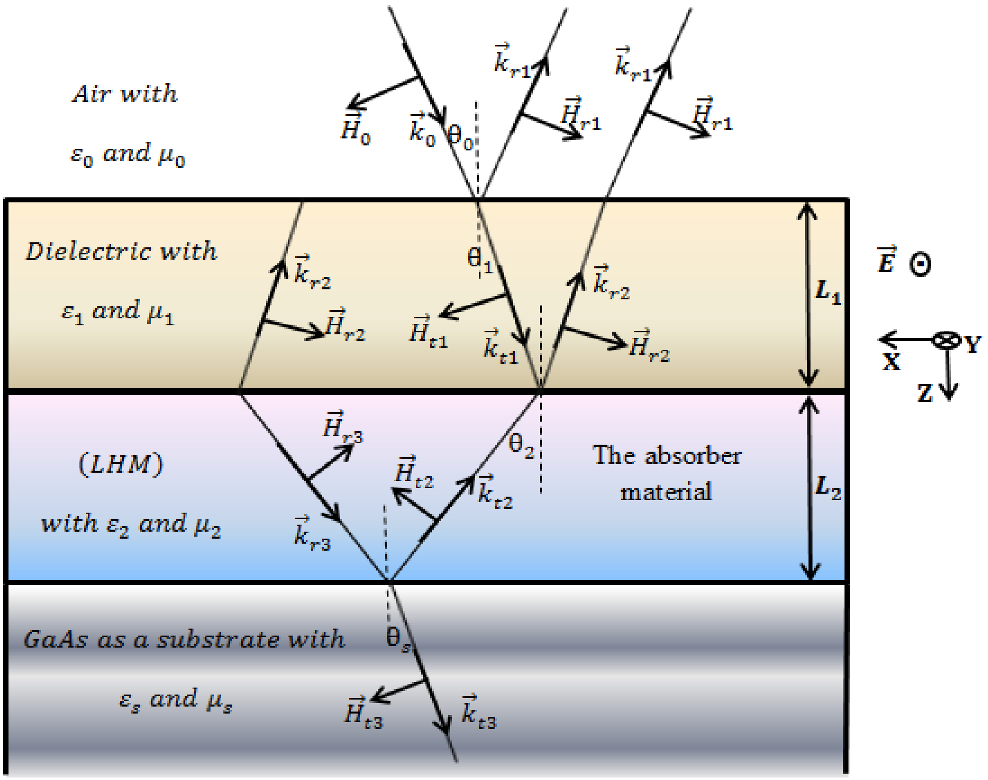

Fig. 1 – Schematic diagram of the investigated DLARC structure under TE polarization of light.

The angles θ_0, θ_1, θ_2 and θ_s shown in Fig. 1 represent the angles of incidence in air, refraction in the dielectric, refraction in the LHM, and refraction in the substrate respectively. The SiN_x layer takes the thickness $L_1 = 70$ nm and the thickness of the LHM is $L_2 = 3.97$ μm [26, 31]**.** Following the method and approach in [21, 29, 30], the 2×2 transfer matrix is easily generated by connecting the field components at two sequential boundaries as follows:

$$\boldsymbol{M}_k = \begin{bmatrix} \cos(\delta_k) & \dfrac{\mathrm{i}\sin(\delta_k)}{\eta_k} \\ \mathrm{i}\,\eta_k \sin(\delta_k) & \cos(\delta_k) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} E_a \\ B_a \end{bmatrix} = \boldsymbol{M}_k \begin{bmatrix} E_b \\ B_b \end{bmatrix} \tag{2}$$

where $(\delta_k = 2\pi n_k d_k \cos n(\theta_k)/\lambda)$ is the phase difference, d_k its thickness, η_k is the so-called optical admittance, and θ_k is the propagation angle following Snell's law.

$$n_0 \sin\theta_0 = n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3 \quad (3)$$

In the case of the oblique incidence (θ_0), the admittance values of transverse electric (TE) and transverse magnetic (TM) are different [21, 29, 30]. For a given m number of layers, the overall transfer matrix ($\boldsymbol{M}_T$) is defined in terms of an individual matrix as follows:

$$\boldsymbol{M}_T = \boldsymbol{M}_1 \boldsymbol{M}_2 \boldsymbol{M}_3 \ldots \boldsymbol{M}_m = \prod_{k=1}^{m} \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (4)$$

The elements of the system of transfer matrix are used to calculate the reflection coefficient and the reflectance as follows [15–18]:

$$r = \frac{m_{11}\eta_0 + m_{12}\eta_0\eta_s - m_{21} - m_{22}\eta_s}{m_{11}\eta_0 + m_{12}\eta_0\eta_s + m_{21} + m_{22}\eta_s}. \quad (5)$$

where m_{11}, m_{12}, m_{21}, and m_{22} are the elements of the characteristic matrix resulting from multiplying the two matrices representing the two layers.

In the case of a solar cell, the total reflectance (R) and transmittance (T) are defined as the average of both average values R^{TE} and R^{TM}, T^{TE} and T^{TM} are written as:

$$R = \frac{R^{TE} + R^{TM}}{2}, \text{ and } T = \frac{T^{TE} + T^{TM}}{2}. \quad (6)$$

3. RESULTS AND DISCUSSIONS

After simulation and computation, we focus on the average absorption for TE and TM polarization that has been computed as a function of physical parameters. The obtained results for TE and TM polarizations are then fed into equation 6, to extract the average of absorption by applying the conservation law of the energy, the average absorbance is written as

$$A_{ave} = 1 - R - T \quad (7)$$

To determine the optimal value of ε_2 for the LHM layer, ε_1 for SiN_x layer is fixed at 3.24. The following figures show total reflectance (R) and transmittance (T), and absorbance against wavelength for different ε_2 [26, 31].

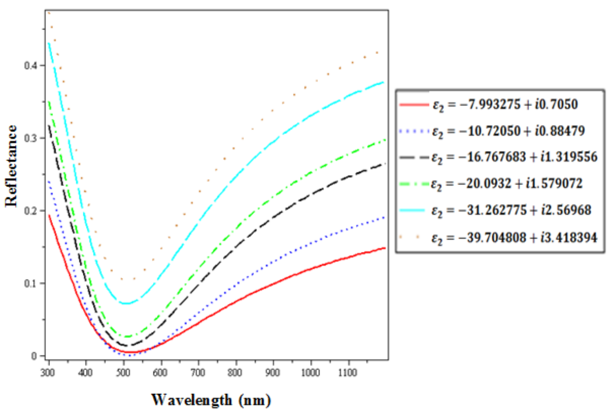

Fig. 2 – Average of reflectance versus the wavelength for different ε_2 for the LHM with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm and $L_2 = 3.97$ μm under normal incidence.

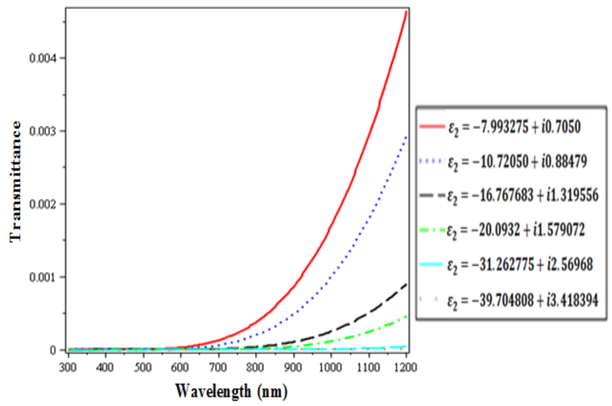

Fig. 3 – Average of transmittance versus the wavelength for different ε_2 for the LHM with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm and $L_2 = 3.97$ μm under normal incidence.

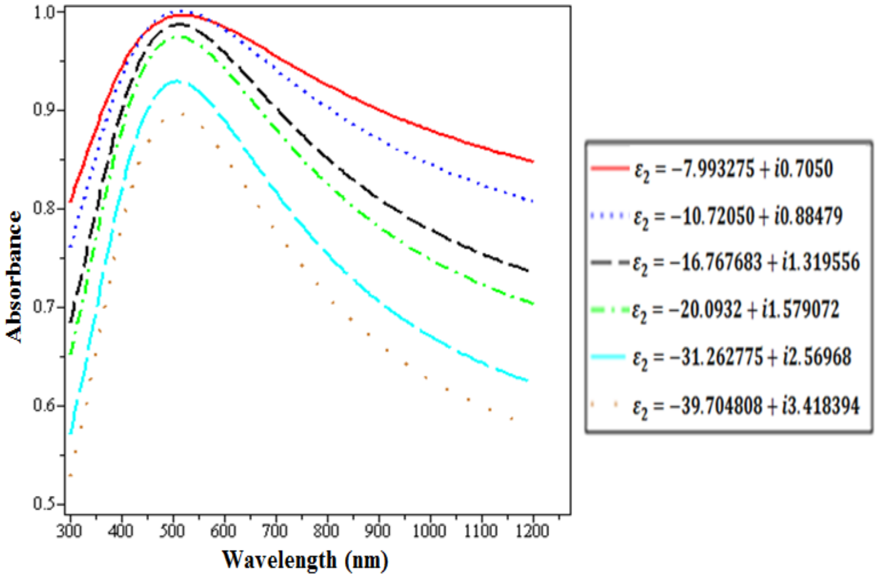

Fig. 4 – Average of absorbance versus the wavelength for different ε_2 for the LHM with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm and $L_2 = 3.97$ μm under normal incidence.

Under normal incidence all of the average results of the two polarizations are matching with TE and TM polarizations, so all of the values of ε_2 in the previous figures can give good results with the same, ε_1 for the SiN_x layer. These figures clearly show that the best performance of the proposed solar cell structure is related to $\varepsilon_2 = -7.993275 + i\,0.7050$ and $\varepsilon_2 = -10.720504 + i\,0.884790$ in terms of maximum absorption and minimal reflection. Figures 5 and 6 illustrate the effect of the angle of incidence on the average absorbance for two LHMs and for different incidence angles. Figure 5 uses $\varepsilon_2 = -7.993275 + i\,0.7050$ for the LHM which gives acceptable results with angles of incidence less than 60°, while Fig. 6 computed for $\varepsilon_2 = -10.720504 + i\,0.884790$ shows small difference in the upper and lower values of absorption.

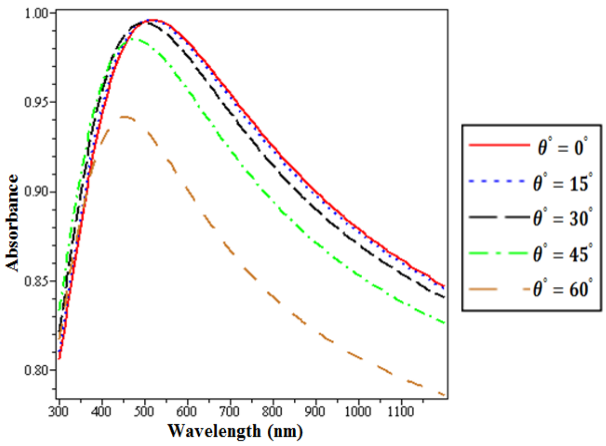

Fig. 5 – Average of absorbance versus the wavelength for different angles of incidence with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm, $L_2 = 3.97$ μm and $\varepsilon_2 = -7.993275 + i\,0.7050$.

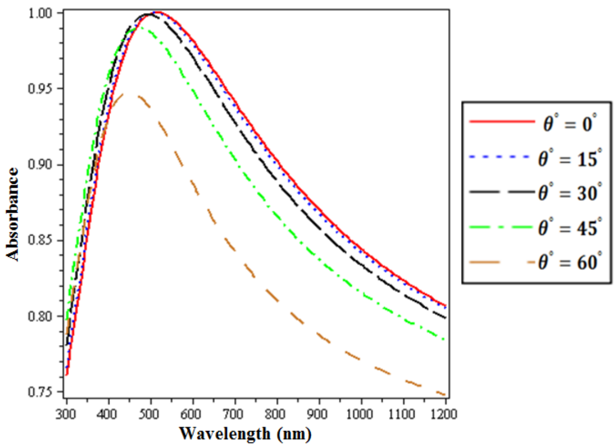

Fig. 6 – Average of absorbance versus the wavelength for different angles of incidence with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm, $L_2 = 3.97$ μm and $\varepsilon_2 = -10.720504 + i\,0.884790$.

Figures 7 and 8 display the variation of the average absorption as a function of the angle of incidence for selected light wavelengths and for the two previously used values of ε_2. These confirm the previous results, where the average absorption falls significantly when the angle of incidence gets more than 60°. Both figures show the maximum absorption has been observed at the wavelength λ_0, 500 nm.

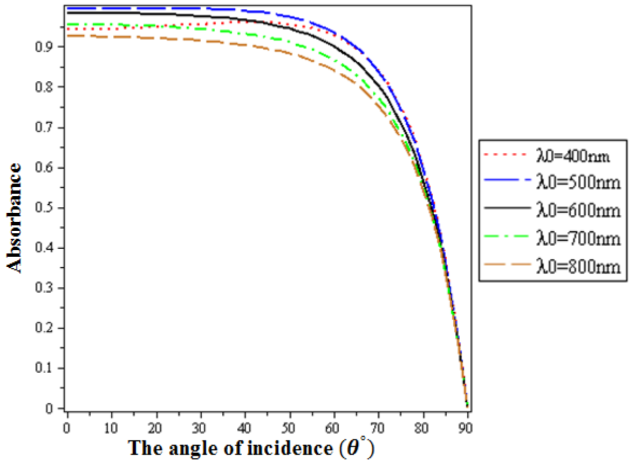

Fig. 7 – Average of absorbance versus the angles of incidence for different wavelengths with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm, $L_2 = 3.97$ μm and $\varepsilon_2 = -7.993275 + i\,0.7050$.

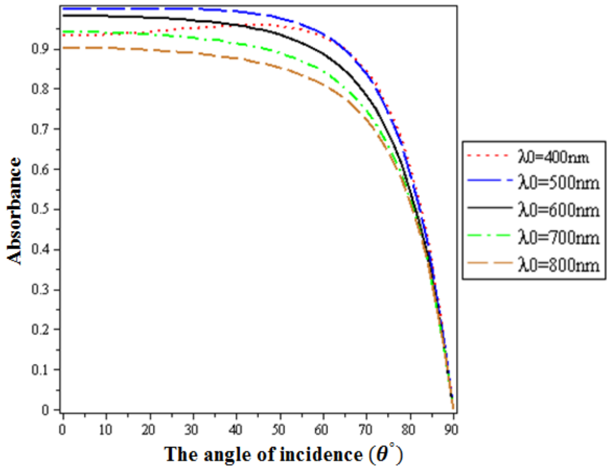

Fig. 8 – Average of absorption versus the angles of incidence for different wavelengths with $\varepsilon_1 = 3.24$, $L_1 = 70$ nm, $L_2 = 3.97$ μm and $\varepsilon_2 = -10.720504 + i\,0.884790$.

It has been observed that the absorption of the proposed structure can be tuned and controlled by the left handed material used and the light incident angle on the structure.

4. CONCLUSIONS

In this study, the double-layer antireflection coating (DLARC) incorporating LHM is theoretically and numerically designed and investigated by the transfer matrix method to further increase light absorption into the absorber layer. There are several values of ε_2 for the LHM layer that gives good maximum absorptions. As the angle of the light incidence increases, the maximum absorption decreases and shifts slightly towards higher energy spectra, and the angles until 60° can give an acceptable absorption for solar cells.

ACKNOWLEDGMENTS

The authors are grateful to the Council for at-risk academics for financial support.

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Received March 2, 2023