Hala J. El-Khozondar, Rifa J. El-Khozondar, Abhishek Sharma, Kawsar Ahmed and Vigneswaran Dhasarathan*

Highly Efficient Solar Energy Conversion Using Graded-index Metamaterial Nanostructured Waveguide

https://doi.org/10.1515/joc-2019-0285
Received November 30, 2019; accepted January 28, 2020

Abstract: In this paper, a graded-index metamaterial (GIM) nanostructured waveguide is proposed to enhance the performance of solar cells via a tunable absorption spectrum. The proposed four-layer nanostructured waveguide consists of two GIM and SiN_x films which are squeezes between glass substrate and air. Using a transmission matrix method, the transmittances as well as the reflectance are calculated for different film thicknesses, refractive indices and incidence angles. We demonstrate that the reflectance is nearly zero where SiN_x refractive index is 2.2 in vicinity of 620 nm. As the incident angle increases, the minimum reflectance wavelength blueshifts and slightly increase in the value. In addition, the variation in the minimum reflectance due to a change in the thickness of SiN_x layer studied in detail. We show that the absorbance of a solar cell can be easily controlled by varying refractive index and/or thickness of SiN_x layer in the proposed nanostructure. The result shows that the best efficiency occurs at normal incidence, $n_2 = 2.2$, and $d_2 = 30$ nm.

Keywords: metamaterial, graded structure, reflectance, refractive index

***Corresponding author: Vigneswaran Dhasarathan,** Division of Computational Physics, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City 700000, Vietnam; Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City 700000, Vietnam, E-mail: vigneswaran.d@tdtu.edu.vn
Hala J. El-Khozondar, Electrical Engineering department, Islamic University of Gaza, Gaza, Palestine, E-mail: hkhozondar@iugaza.edu.ps
Rifa J. El-Khozondar, Physics Department, Al-Aqsa University, Gaza, Palestine, E-mail: rifa20012002@yahoo.com
Abhishek Sharma, Department of Electronics and Communication, sri sai university, c/o SSU Palampur, sungal, padiarkhar, palampur kanggra, Palampur, Himachal Pradesh 176081, India, E-mail: er.abhisheksharma07@gmail.com
Kawsar Ahmed, Department of Information and Communication Technology, Mawlana Bhashani Science and Technology University, Santosh, Tangail 1902, Bangladesh, E-mail: k.ahmed.bd@ieee.org

1 Introduction

Due to environmental problems associated with the traditional sources of energy (fossil fuels) such as global warming and water contamination, energy policy makers are seeking for an environmental-friendly source of energy [1]. Solar energy is the most promising type of renewable energy which is clean and environmentally safe. Solar energy can provide unlimited amount of energy while reducing the carbon footprint and greenhouse gases in the atmosphere [1, 2]. Photovoltaic (PV) cell is the building block for a solar energy generation system as it absorbs light and converts it to the electrical energy [1, 2].

Several works have been conducted to increase the efficiency of the PV cells. To decrease the reflection of light at the surface of the PV, antireflection coating (ARC) is used [1]. An important example of ARC is SiNx for its high refractive index [2]. The refractive index of SiN depends on the actual fabrication process and has an interval from 1.77 to 2.5 [3]. In addition, researchers who are seeking minimum reflectance at PV surface, introduce new structure, which involve metamaterial (MTM). Metamaterial is a novel material with negative refractive index which can have different refractive indices by changing certain parameter as seen in [4–7].

The utilization of MTM for energy harvesting and design of PV cells is an interesting field of research. In 2012 [8], using Ni and SiN based periodic MTM, a solar absorption efficiency of 77 % and 85 % observed in solar spectrum and visible region, respectively. In 2015 [9], the efficiency further improved to 99.99 % and 99.90 % at 543.75, 663.75 THz range after adjusting the geometry in nanostructured MTM periodic waveguide. In recent years, the same absorption efficiency also observed for proposed MTM structure in visible and infrared region [10]. Recently, silicon-based MTM with dielectric base [11] has been reviewed for visible range applications which revealed that MTM with its interesting optical properties can pave the way for important applications including sensing, nonradioactive data transferring and nano-photonics.

Currently, design of MTMs as emitter has been done in 1D structures based on the W-HfO_2 layer, which shows the emission properties at the maximum temperature of 1400 [12]. In this article, a planar waveguide structure with the combination of SiN and glass substrate is proposed and the effect of refractive indices and incident angles on the transmission and reflection efficiencies in the visible spectral range is studied in detail. Transverse matrix method (TMM) [13–15], a well-known method to analyse the propagation of electromagnetic files through stack layers, is used in the calculations of transmission and reflection of the proposed solar cell. Next section presents the model and results.

2 Model and results

In this work, a new PV structure using a graded-index metamaterial (GIM) layer is proposed. The schematic of the proposed PV that consists of SiN_x thin film deposited on glass and covered by GIM bounded by air is illustrated in Figure 1.

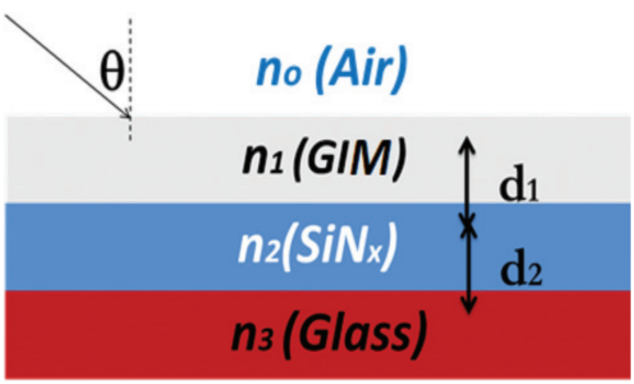

Figure 1: The schematic of the proposed nanostructured solar cell.

In the proposed structure n_0, n_1, n_2, and n_s are refractive indices for air, GIM, SiN_x and glass, respectively. Here, the GIM layer is assumed to have a graded index with thickness d_1, and SiN_x has a thickness of d_2 and its refractive index can take different values depending on the doping ratio. The values of the film thicknesses (d_1 and d_2) are chosen to be equal to 50 and 40 nm, respectively. The light is considered to shine on the PV at oblique incidence with different incidence angles (θ).

For oblique incidence, the optical reflectance and admittance for the kth layer including negative index materials with graded index are derived in the literature [16, 17] for both transverse electric field polarization (TE) and transvers magnetic field polarization (TM) as follows:

$$\gamma_k^{TE} = \frac{1}{\eta_0 \mu_k} n_k \cos\theta_k \tag{1}$$

$$\gamma_k^{TM} = \frac{1}{\eta_0 \mu_k} \frac{n_k}{\cos\theta_k} \tag{2}$$

where θ_k is related to θ_0 by

$$n_0 \sin\theta_0 = n_k \sin\theta_k;\ k = 1, 2, \ldots m \tag{3}$$

The 2 × 2 transfer matrix (M_k) that relates the field components at two successive boundaries is

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

$$\begin{bmatrix} E_a \\ B_a \end{bmatrix} = M_k \begin{bmatrix} E_b \\ B_b \end{bmatrix} \tag{5}$$

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

$$M_T = M_1 M_2 \ldots M_m = \prod_{k=1}^{m} M_k \tag{6}$$

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

$$r = \frac{E_{r1}}{E_0} \tag{7}$$

The sunlight consists of both TE and TM polarizations. Thus, the total reflectance R for the solar cell is defined as the average of both values R^{TE} and R^{TM}

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

And the total transmittance is also defined as the average of both values T^{TE} and T^{TM}

$$T = \frac{T^{TE} + T^{TM}}{2} \tag{9}$$

Eqs. (8) and (9) are solved numerically using the software Maple 17 to verify the characteristics of the proposed PV cell. The thicknesses are chosen such that d_1 = 40 nm and d_2 = 40 nm. The spectral response of SiN_x goes from 300 to 1200 nm [4]. Thus, this range is taken to limit the spectrum of the incident light. In the calculations, only normal incidence is considered.

Figure 2 exhibits the total reflectance *R* at different values of n_2: 2.5, 2.4, 2.3 and 2.2 and GIM has $n_1 = -2 + \Delta(n)$ at normal incidence, where Δ(n) is chosen to have quadratic dependence on the layer thickness.

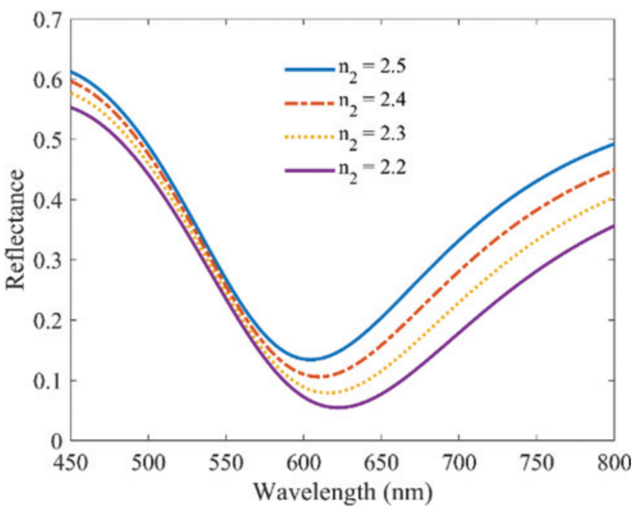

Figure 2: The reflectance is calculated for $n_1 = -2 + \Delta(n)$, under normal incidence at different values of n_2.

We notice that the spectral approaches minimum value when n_2 = 2.2 for λ around 620 nm and all other curves maintain a reflectance lower than 0.2. Our results are considered to be good in comparison with structure has one or two ARC layers [4].

The effect of incident angle on the reflectance is shown in Figure 3, where the value of n_2 = 2.2. From Figure 3 one can easily notice that as θ increases the minimum reflectance slightly increases and the value of λ at which minimum occurs shifts toward smaller values.

For n_2 = 2.2, normal incidence, and d_1 = 40 nm, the average reflectance and average transmittance are performed for different values of d_2 as in Figures 4 and 5.

We notice that as the valued of d_2 decreases, the values of minimum reflectance value decreases towards zero and the corresponding wavelength shifts to higher wavelength (see Figure 5). Similarly, maximum transmittance value increases as d_2 decreases and the corresponding wavelength shifts to higher wavelength (see Figure 4). In our model, the minimum reflectance and maximum transmittance occur at normal incidence, n_2 = 2.2, and d_2 = 30 nm.

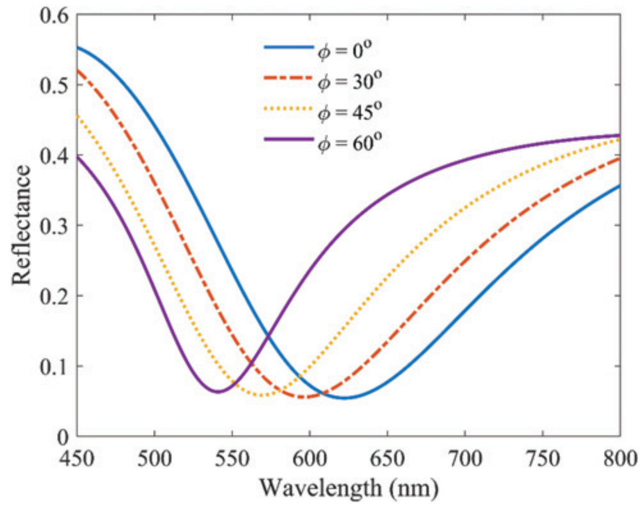

Figure 3: The reflectance is calculated for $n_1 = -2 + \Delta(n)$ and n_2 = 2.2 at different incident angles.

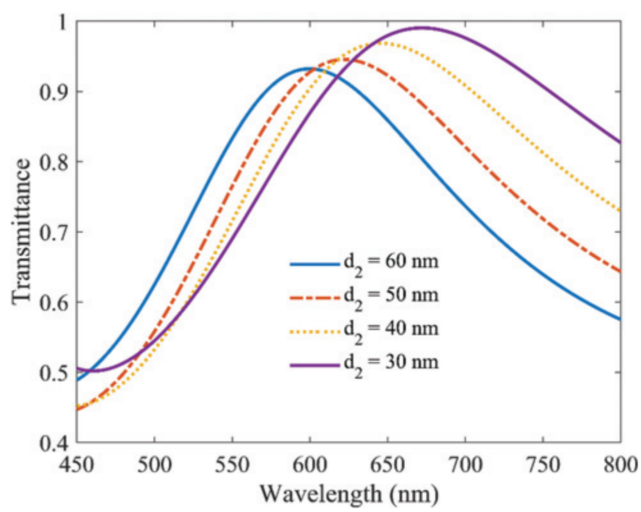

Figure 4: The transmittance is calculated at normal incidence for $n_1 = -2 + \Delta(n)$ and n_2 = 2.2 at different values of d_2.

The comparisons between different reflectance of the transmitted light from PV cells with different structures are presented in Table 1. Table 1 shows that different structures give different values of reflectance around certain wavelength.

The obtained values are good result compared to other values. This due to the graded-index structure can trap light more efficiently than other structures.

3 Conclusion

In this work, a four-layer nanostructured PV cell is proposed using GIM. The nanostructured waveguide reflectance and

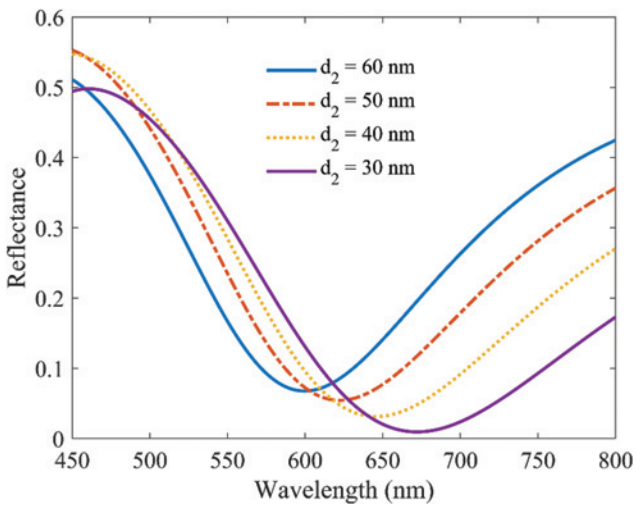

Figure 5: The reflectance is calculated at normal incidence for $n_1 = -2 + \Delta(n)$ and $n_2 = 2.2$ at different values of d_2.

Table 1: Presents a comparison between our results and other papers.

Work	Value of minimum reflection (%)	Wavelength at minimum reflection (nm)
This work	0.9	670.2
Beye et al. [4]	Less than 5	600
El-Alamassi et al. [7]	Less than 2	600
El-Khozondar et al. [13]	Less than 1	500
Shabat et al. [14]	Less than 2	600
El-Khozondar et al. [15]	Less than 1	600

absorbance are studied using TMM method. Results show that the reflectance shows a minimum around 620 nm at a SiN_x refractive index of 2.2. Moreover, as incident angle increases, the minimum value of reflectance blueshifts and become almost zero with SiN_x layer thickness of 30 nm. We clearly demonstrate that the solar cell reflectance and transmittance can be controlled by changing refractive index, incident angle and layer thickness in the proposed nanostructure which can have important applications in harvesting the solar energy. The result show that the best efficiency occurs at normal incidence, $n_2 = 2.2$, and $d_2 = 30$ nm.

Acknowledgements: The authors would like to express their sincere thanks to Prof. Dr Truong Khang Nguyen, Division of Computational Physics, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam for giving his value suggestion, comments and support to complete this work as effective. Authors also would like to thank Dr Yashar E. Monfared from Department of Physics and Atmospheric Science, Dalhousie University, Halifax, NS, Canada for giving their technical support and help in reviewer response.

References

1. Lee HC, Su YK, Chuang WK, Lin JC, Huang KC, Cheng YC, et al. Discussion on electrical characteristics of i-In0.13Ga0.87N p-i-n photovoltaics by using a single/multi-antireflection layer. Solar Energy Mater Sol Cells. 2010;94:1259–62.
2. Lee Y, Gong D, Balaji N, Lee Y, Yi J. Stability of SiN_x/ SiN_x double stack antireflection coating for single crystalline silicon solar cells. Nanoscale Res Lett. 2012;7:50–6.
3. Kim DS, Yoon SG, Jang GE, Suh SJ, Kim H, Yoon DH. Refractive index properties of SiN thin films and fabrication of SiN optical waveguide. J Electroceram. 2006;17:315–18.
4. Beye M, Faye ME, Ndiaye A, Ndiaye F, Maiga AS. Optimization of SiNx single and double layer ARC for silicon thin film solar cells on glass. Res J Appl Sci Eng Technol. 2013;6:412–16.
5. El-Khozondar HJ, El-Khozondar RJ, Zouhdi S. Tunable MTMs consists of a single-walled nanotube thin film waveguide covered by nonlinear cladding. Appl Phys A. 2015. DOI:10.1007/s00339-015-9007-5.
6. Werner DH, Kwon D, Khoo I, Kildishev AV, Shalaev VM. Liquid crystal clad near-infrared metamaterials with tunable negative-zero positive refractive indices. Opt Express. 2011;15:3342–7.
7. El-Alamassi DM, El-Khozondar HJ, Shabat MM. Efficiency enhancement of solar cell using metamaterials. Int J Nano Stud Techno (IJNST). 2015;4:84–7.
8. Liu Y, Chen Y, Li J, Hung T, Li J. Study of energy absorption on solar cell using metamaterials. Solar Energy. 2012;86:1586–99.
9. Rufangura P, Sabah C. Dual-band perfect metamaterial absorber for solar cell applications. Vacuum. 2015;120:68–74.
10. Mulla B, Sabah C. Perfect metamaterial absorber design for solar cell applications. Waves Random Complex Media. 2015;25:382–92.
11. Ospanova AK, Stenishchev IV, Basharin AA. Anapole mode sustaining silicon metamaterials in visible spectral range. Laser Photon Rev. 2018;12:1–6.
12. Chirumamilla M, Krishnamurthy GV, Knopp K, Krekeler T, Graf M, Jalas D, et al. Metamaterial emitter for thermophotovoltaics stable up to 1400°C. Sci Rep. 2019;9:7241.
13. El-Khozondar HJ, Alshembari AA, Shabat MM, Koch AW. Two layers corrugated semiconductor solar cell. Optik. 2019;181:933–40.
14. Shabat M, El-Khozondar HJ, AlSembari AN, El-Khozondar RJ. Transfer matrix method application on semiconductor based solar cell characteristics measurements. J Mod Phys B. 2018;32:1850346.
15. El-Khozondar HJ, El-Khozondar RJ, Shabat M, Schaadt D. Solar cell with multilayer structure based on nanoparticles composite. OPTIK. 2018;166:127–31.
16. Al-Turk S. Analytic optimization modeling of anti-reflection coating for solar cells. Master thesis, MacMaster University, 2011: Open Dissertations and theses.
17. Lequime M, Gralak B, Guenneau S, Zerrad M, Amra C. Optical properties of multilayer optics including negative index materials. Physics-Optics, arXiv:1312.6288v1, 21 December 2013.