A 650 nm design for multilayer anti-reflection coating in GaAs solar cells

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Theoretically optimized triple layer antireflection coating can be replaced with four layer LHLH structure around the designed wavelength. In this paper, triple layer and its four layer equivalent structure have been utilized as antireflection coating of GaAs solar cell and the reflectance coincidence of these structures is proved. The wavelength of 650nm has been assumed for design of multilayer structure. Also, the six layer antireflection coating is made with inserting one more HL pair in the structure. We design multilayer structures by introducing X parameter which describes 4- and 6-member set of thicknesses and finding the optimum combination of thicknesses. Simulation results confirm that the optimum case of six layer structure presents better performance in comparison with the best case of four layer coating.

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1. Introduction

High reflectivity of materials such as silicon and GaAs which act as active layers of solar cells has a harmful effect on photovoltaic characteristics. For example, theoretical calculations show that 35% of incident light is reflected from the surface of silicon substrate [1]. Utilizing anti-reflection coating (ARC) on top of the solar cells is one of the light trapping techniques in order to decrease the escape of photons. Nowadays, the AR coatings are key components of recent-fabricated solar cells. In recent years, the multi-layer antireflection coatings are preferably used in III-V single and multijunction solar cells [2-4]. The most applicable materials used as single and double layer ARCs are ZnS and MgF_2/ZnS, respectively [2], [5], [6]. Antireflection coatings with more than two layers are not practically used in solar cells. The main reason that decreases the application of triple layer ARCs is to find a matched material as the third layer between two upper and lower layers. This material should be matched with the refractive index derived from theoretical calculations. Also, the chosen material has to show admissible chemical and mechanical stability. One of the methods in order to solve this problem is changing the fabrication process. Indeed, the materials can be fabricated with changing the composition of available materials in order to achieve the new materials with desired refractive indices [7]. Also, the middle layer in Low/Medium/High triple layer structure can be replaced with a reverse composition of lower and higher index materials.

In this paper, possibility of replacing triple layer ARC with 4 layer LHLH structure is proved. Also, the six layer equivalent structure is made with inserting one more HL pair and showed better performance in comparison with best case of 4 layer ARC. In section 2, theoretical background of antireflection coatings and transfer matrix method is presented. The paper will be followed with design characteristics and simulation results of four and six layer structure. Finally, the electrical performance of proposed structure will be discussed.

2. Theoretical background

Antireflection coating layers are designed in order to decrease the escape probability of incident photons from cell's surface. The refractive index and thickness are key parameters in designing ARCs. A simple layer ARC is characterized by refractive index of

$$n_{ARC} = \sqrt{n_0 n_{Sub}} \tag{1}$$

and thickness of

$$T_{ARC} = \frac{\lambda_0}{4 n_{ARC}} \tag{2}$$

where n_0 and n_{Sub} are the refractive indices of air and substrate, respectively [8].

The number of photons reflected from the surface of solar cells will be more decreased by utilizing antireflection coatings with higher number of layers. The refractive index of m^{th} layer of M-layer antireflection coating with n_{Sup} and n_{Sub} as the refractive index of the superstrate and substrate layers is given as:

$$n_m = n_{Sup}^{\left(\frac{M+1-m}{M+1}\right)} \, n_{Sub}^{\left(\frac{m}{M+1}\right)} \tag{3}$$

Fig. 1 shows an M-layer structure with different refractive indices which are increased from air to substrate.

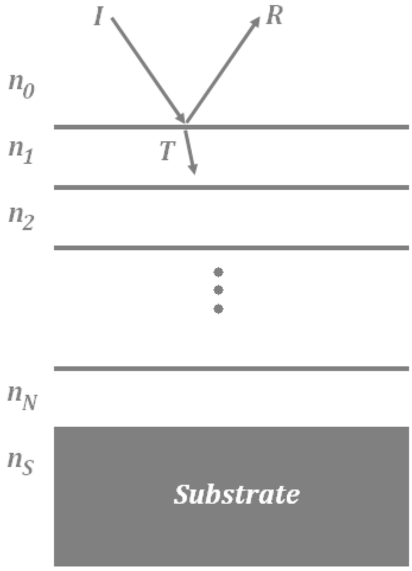


Fig. 1. Reflected and transmitted light from a layered media.

The equations between incident, reflected and transmitted light can be deduced with transfer matrix method. Such transfer matrix shows the relation of electromagnetic fields' amplitudes in the interfaces and can be presented as follows [5]:

$$M_{eq} = \prod_{j=1}^{j=N} \begin{bmatrix} \cos\varphi_j & \left(\dfrac{i}{n_j^{eff}}\right)\sin\varphi_j \\ i\ n_j^{eff}\ \sin\varphi_j & \cos\varphi_j \end{bmatrix} \tag{4}$$

where n_j is the j^{th} layer refractive index, $\varphi_j = 2\pi n_j^{eff}\ d_j / \lambda$ is the j^{th} layer phase thickness and d_j is the j^{th} layer thickness. n_j^{eff} is effective refractive index which can be introduced with $n_j^{eff} = n_j \cos\theta_j$ for parallel polarization and $n_j^{eff} = n_j / \cos\theta_j$ for the normal polarization with θ_j as the incident angle of j^{th} layer.

3. Four layer equivalent structure

As mentioned, the refractive index of middle layer in triple layer ARCs can be determined with the previously stated theoretical calculations. However, it is hard to find available materials with desired refractive index. So, triple layer anti-reflection coating can be substituted with the LHLH equivalent structure. This equivalency can be seen in a design wavelength which is the peak wavelength of solar spectrum. This will be so desirable if the reflectance curve of triple layer and 4 layer LHLH structures could be similar in the higher range of wavelengths. Fig. 2 shows the basic structures of triple layer and LHLH ARC.

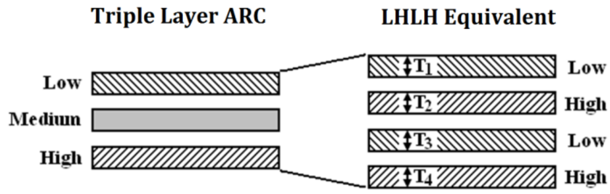


Fig. 2. Basic structure of triple layer ARC and its LHLH equivalent.

As can be seen, LHLH structure is a reverse composition of higher and lower index materials. The high- and low-index materials are chosen as MgF_2 (1.39) and TiO_2 (2.44), respectively. The medium refractive index corresponded to middle layer can be theoretically calculated as 1.84. Although, it is hard to find a completely matched material with theoretically achieved refractive index, but between the real and available materials, Al_2O_3 is the best candidate for middle sub-layer of triple layer antireflection coating. We simulated the reflectance of both of triple layer and LHLH structure. The simulated structures are $MgF_2/Al_2O_3/TiO_2$ and $MgF_2/TiO_2/MgF_2/TiO_2$ (LHLH) for triple layer and equivalent structure, respectively. The structure is designed to absorb the photons in peak region of solar spectrum which are corresponded to the wavelength range of 650nm. Refractive index and layer thickness are the important parameters that affect the optical performance of antireflection coatings. The former is one of the inherent characteristics of each material which should be considered in design of structure as an invariant parameter. However, the thickness of different layers can be changed in order to achieve the optimum configuration. The purpose of these simulations is to find best thicknesses of LHLH sublayers in order to access the perfectly matched structure with triple layer ARC. In first step, the reflectance difference of 4 layer and triple layer ARC versus the thicknesses of layers is simulated. Fig. 3 presents the reflectance difference ($\Delta R = R_{4L} - R_{3L}$) curve versus X parameter. Each X is the symbol of a 4-member set for thicknesses of LHLH equivalent sublayers.

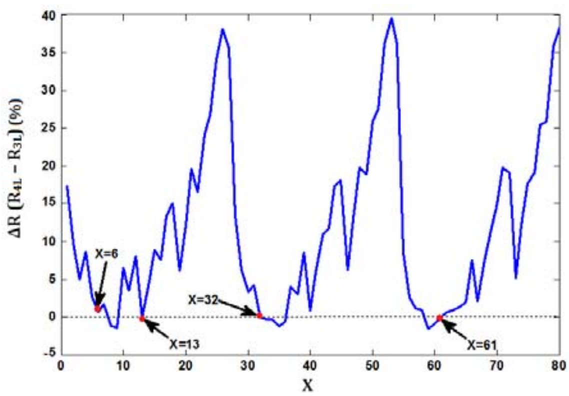
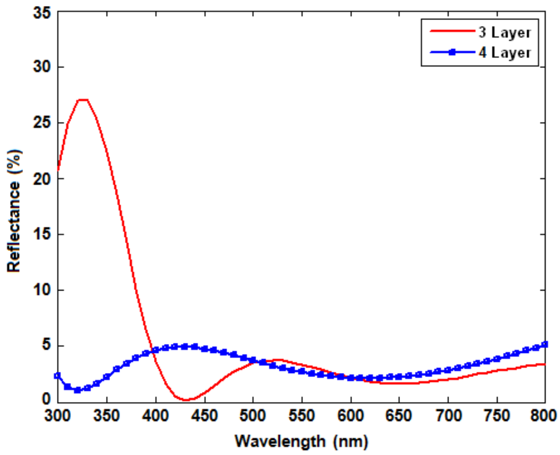
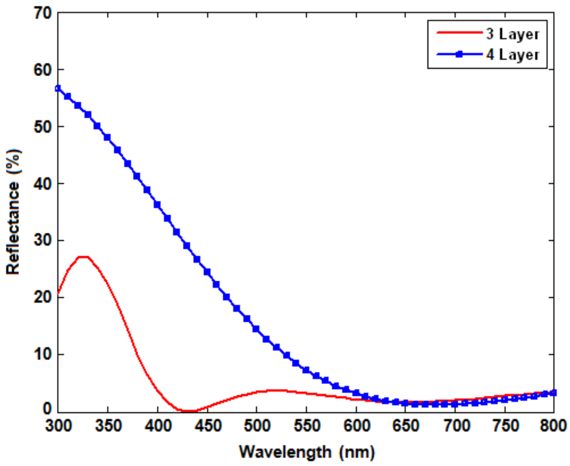


Fig. 3. The difference of reflectance between triple layer ARC and its 4 layer equivalent structure.

The layer thicknesses of 4 layer structure are changed to make different sets. According to this fact that the design of structure is based on a single wavelength (650nm), the oscillations that can be seen in the curve are related to the periodic behavior of 4 layer configuration against wavelength, in accordance with Eq. (2). Therefore, the difference between reflectance of two mentioned structures is varied in a wide range against small variation of X parameter. As can be seen in Fig. 3, four values of X are achieved as the lowest difference points between reflectance of mentioned structures. The variations of reflectance versus optical wavelength for these thicknesses is simulated and presented in Fig. 4.



(a)



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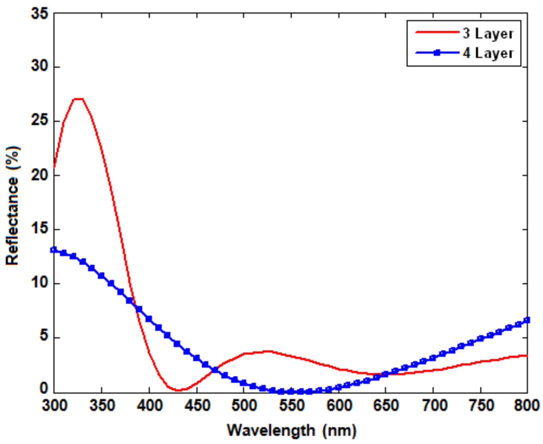

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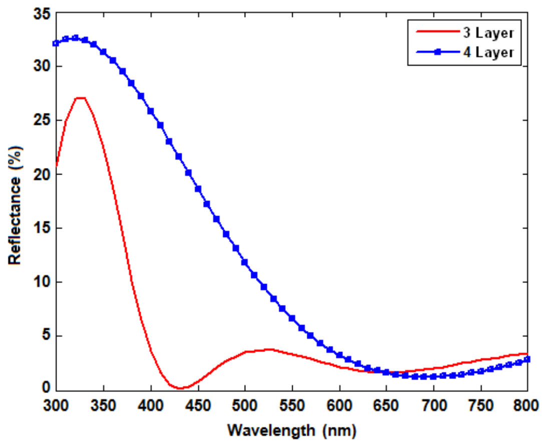


(d)

Fig. 4. The curve of reflectance for triple layer ARC and its LHLH equivalent in: (a) X=6 (with $T_1/T_2/T_3/T_4$: 10/10/30/50); (b) X = 13 (10/30/30/10); (c) X = 32 (30/10/30/30); (d) X=61 (50/10/50/10).

Although all the curves of Fig. 4 imply that the designed equivalent structure shows the same reflectance as triple layer near 650nm, but Fig. 4a shows the best case of structure for X=6 (means that the thicknesses of four sublayers referred to $T_1/T_2/T_3/T_4$ are equal to 10/10/30/50). In this figure, the curve of reflectance for LHLH equivalent structure is almost same as triple layer ARC in a wide range of higher wavelengths and smaller than that in the lower wavelengths. In addition, the proposed structure with thicknesses of 10/30/30/10 (X=13) shows the good coincidence in high wavelengths, but this structure cannot be the desired equivalent of triple layer ARC in lower wavelengths. We utilized the different cases of mentioned structure as the ARC layer in GaAs single junction solar cell. The total structure of simulated solar cell is proposed in Fig. 5.

Anti-Reflection Coating			
Window	p-$Al_{0.85}Ga_{0.15}As$	1×10^{18} cm^{-3}	0.1μm
Emitter	p-GaAs	1×10^{18} cm^{-3}	0.5μm
Base	n-GaAs	8×10^{16} cm^{-3}	3.5μm
BSF	n-$Al_{0.2}Ga_{0.8}As$	5×10^{17} cm^{-3}	0.1μm
n-GaAs Substrate			

Fig. 5. GaAs cell structure.

Fig. 6 shows the curve of cathode current for GaAs solar cell with triple layer and four cases of 4 layer LHLH antireflection coatings derived from Fig. 3.

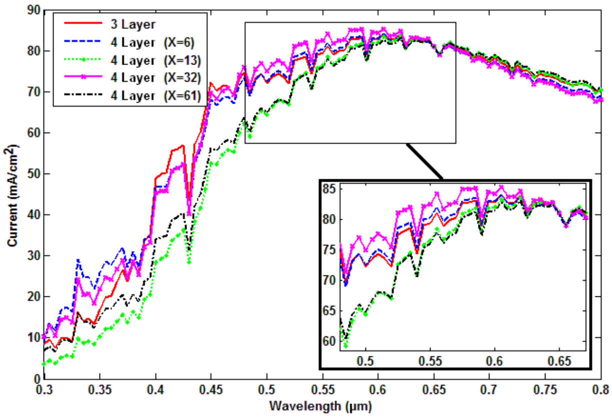


Fig. 6. The cathode current of total cell versus optical wavelength for triple layer and 4 layer equivalent in different cases of layer thicknesses.

Fig. 6 explicitly proves the highest nearness of 4 layer equivalent structure with X=6, 13, 32, 61 to triple layer ARC. The projection of figure in a wide wavelength range around 650nm that is presented in the inset, shows the coincidence of X=6 ($T_1/T_2/T_3/T_4$: 10/10/30/50) LHLH structure with its triple layer counterpart. Also, all of the configurations depicted in Fig. 6 follow our design considerations around 650nm, with converging to the same cathode current point as it in triple layer ARC. Therefore, this figure emphasizes that the curve of 4 layer LHLH structure with X=6 is more equivalent with triple layer ARC.

4. Six layer equivalent structure

The previous section showed that triple layer ARC can be replaced with 4 layer equivalent structure for the higher wavelengths. The simulation results present that the insertion of one more HL pair into proposed structure makes a 6 layer configuration with enhanced performance. The reflectance difference between 6 layer structure and optimized triple layer ARC is shown in Fig. 7.

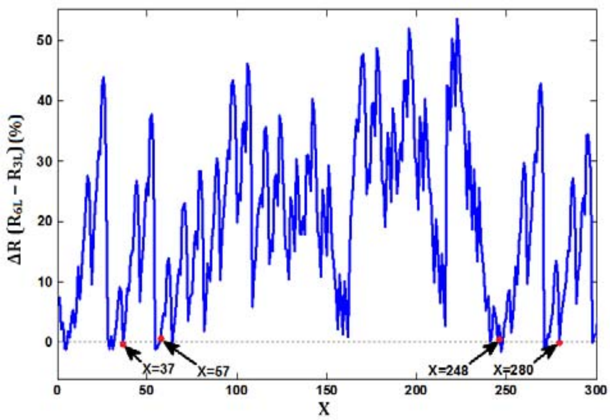


Fig. 7. The difference of reflectance between triple layer ARC and its 6 layer equivalent structure.

Fig. 7 presents four optimum points for the thicknesses of sublayers with the lowest difference between reflectance of six layer structures and triple layer ARC. This curve is simulated for the peak wavelength of solar spectrum. In this figure, a same periodicity can be seen as in Fig. 3. The curve of reflectance depends on the optical wavelength changes is plotted in Fig. 8 for triple layer ARC and four optimum structures of 6 layer structure.

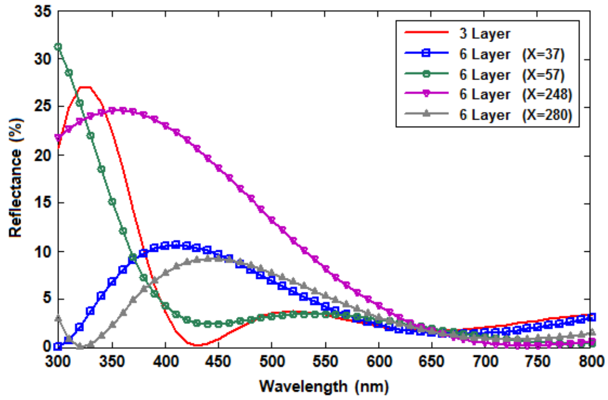


Fig. 8. Comparison of triple layer ARC with 6 layer equivalent with different thicknesses.

Fig. 8 depicts that the 6 layer equivalent structure with X=57 (means that the thicknesses of six sublayers referred to $T_1/T_2/T_3/T_4/T_5/T_6$ are equal to 10/10/50/10/10/50) shows the best coincidence with triple layer ARC even in the lower wavelengths. The comparison of Figs. 4 and 8 shows that the 6 layer structure with X=57 presents better performance than the best case of 4 layer structure with X=6. GaAs solar cell shown in Fig. 5 with 6 layer structure as the antireflection coating is simulated and the cathode current curve for different thicknesses is shown in Fig. 9.

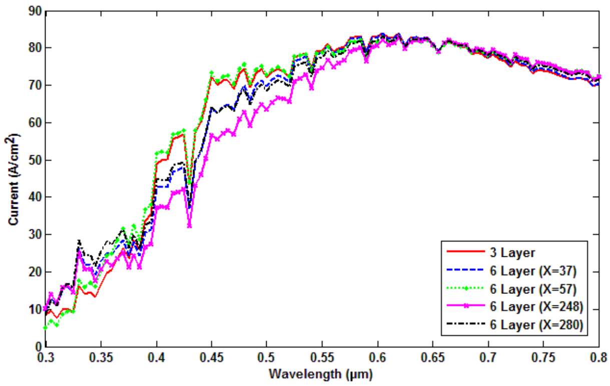
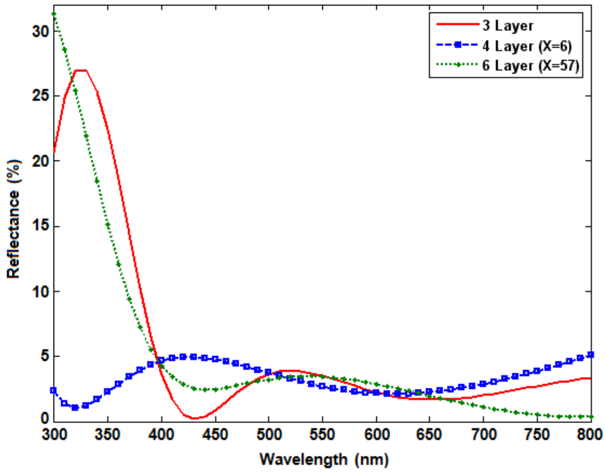


Fig. 9. The cathode current of total cell for triple layer and 6 layer equivalent structure with different thicknesses

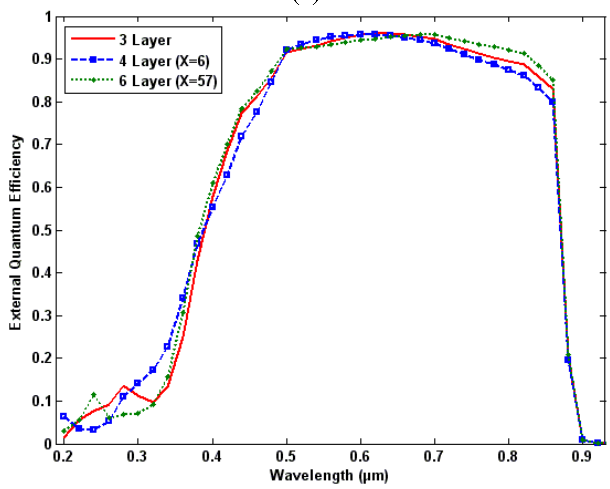
Fig. 9 emphasizes the previous results about the coincidence of six layer structure with triple layer antireflection coating. Also, it is obvious that the 6 layer structure with thicknesses of $T_1/T_2/T_3/T_4/T_5/T_6$: 10/10/50/10/10/50 (X=57) shows the better performance in comparison with another configurations. It should be noted that different configurations of six layer structure are in more pursuing manner with triple layer ARC than its four layer counterpart around 650nm.

5. Discussion

As mentioned above, the best case of layer thicknesses in 4 layer and 6 layer equivalent structure are $T_1/T_2/T_3/T_4$: 10/10/30/50 (X=6) and $T_1/T_2/T_3/T_4/T_5/T_6$: 10/10/50/10/10/50 (X=57), respectively. The performance of these optimum structures can be compared with triple layer ARC. The major effect of antireflection coatings can be observed in the external quantum efficiency (EQE) of solar cell. In fact, the trapped fraction of photons directly affects the EQE. Therefore, the spectrum of reflectance and external quantum efficiency for triple layer ARC along with its best 4- and 6-layer equivalent structures are presented in Fig. 10.



(a)



(b)

Fig. 10. (a) Reflectance and, (b) External quantum efficiency of triple layer ARC along with the best case of 4- and 6-layer equivalent structures versus the optical wavelength.

The curve of EQE shows the equivalency performance of mentioned structures with triple layer ARC. Also, the short circuit current, open circuit voltage, fill factor $((I_m V_m)/(I_{SC} V_{OC}))$ and power conversion efficiency (PCE) of solar cell in triple layer ARC and 4- and 6-layer equivalent structures can be seen in Table 1.

Table 1. Comparison of electrical characteristics between triple layer and best case of 4- and 6-layer equivalent ARCs

ARC Structure	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)
3 Layer	33.35	1.005	87.59	21.5
4 Layer	33.34	1.005	87.44	21.47
6 Layer	33.98	1.006	87.44	21.9

Comparison of electrical characteristics in 3 layer ARC and the best case of 4- and 6-layer equivalent structures confirms our claim about equivalency of two-material structure instead of the theoretically obtained ideal three-material ARC which is composed of an unknown middle layer material. It is obvious that the short circuit current is more affected with changes of antireflection coating than the open circuit voltage. Also, the six layer structure presents even the better values of PCE and J_{sc}.

6. Conclusion

In this paper GaAs solar cell with the ideal triple layer ARC along with its four- and six-layer equivalent structure was simulated. The design of equivalent structures was accomplished by introducing X parameter as the 4- and 6-member set of thicknesses. The optimum cases of mentioned structures were achieved by comparing the reflectance of structures versus variation of X. The simulation results showed that the reflectance of 4 and 6 layer structure with the designed thicknesses is equivalent to triple layer antireflection coating in solar spectrum peak wavelength. Six-layer structure presented the better performance in comparison with optimum case of four-layer ARC. The comparison of electrical characteristics of 3 layer ARC and best case of 4- and 6-layer structures emphasized our claim about the equivalency of 2-material structure instead of theoretically obtained ideal 3-material ARC with an unknown middle layer material.

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