Optimized Single and Double Layer Antireflection Coatings for GaAs Solar Cells

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Abstract- In this paper, the effects of antireflection coatings on the performance of GaAs solar cells are theoretically investigated. Also, the conversion efficiency, short circuit current and open circuit voltage of the solar cell are calculated in various thicknesses and refractive indices of coating materials. Single and double layer coatings are utilized in order to achieve the highest performance. Simulation results show an optimum point for the thickness and refractive indices of the materials used as single and double layer antireflection coatings. Finally, 16.97% conversion efficiency, 27.91mA short circuit current and about 0.944V open circuit voltage are achieved for GaAs single cell with a low 5nm TiO_2 thickness in Al_2O_3/TiO_2 double layer coating. But the lower thickness of TiO_2 increases the incident angle dependency of the reflectance.

Keywords- anti-reflection coating, reflectance, external quantum efficiency, solar cell.

1. Introduction

Solar cells made of III-V direct band gap semiconductors present the higher performance in comparison with silicon cells [1]. The GaAs with energy band gap of 1.424eV is near the optimum material in order to achieve the high efficiencies [2]. Also, the higher absorption and resistivity under high irradiations are the properties of GaAs cells. But the reflection of most semiconductor materials such as GaAs is high about 30-40% [3]. This high reflectivity can be reduced by imposing the anti-reflection coating (ARC) layers on top of the solar cell surface. Optical losses of the solar cells can be divided to three main groups: surface reflection, top contact shading and unwanted rear surface photon transmission. Modifying the top surface can significantly reduce two former groups of optical losses and increase the performance of the cell. It can be achieved by using suitable antireflection layer and contact coverage.

Antireflection coating is a thin dielectric layer with nARC refractive index which is designed to remove the surface reflection via the interference effects. The first ARC was made by Fraunhofer in 1817 [4]. But in spite of this, there were not so much activitiesf on the anti-reflection coatings due to the lack of the necessary instruments for thin film deposition [5]. The first practical solar cell was presented in 1954 without applying any ARCs [6]. In general, the various types of antireflection coatings are single, double and triple layers with constant and graded index of refraction [7]. Generally, ZnS, TiO_2 and CeO2 are used as the materials with high refractive index and MgF2, Al_2O_3 and SiO2 with low refractive index materials in GaAs solar cells [3]. Applying the single layer ARCs reduces the reflection in some special wavelengths. In order to reduce the reflection in higher range of wavelengths, more layers should be utilized. Although increasing the number of layers theoretically diminishes the reflected part of the light, the recent experimental reports of solar cells apply the single and double layer coatings because of the higher complexity of multilayer coatings [1]. There are some problems of utilizing the multilayer coatings such as fabrication issues and finding suitable materials as the middle layer with desirable refractive indices. Multilayer coatings should approximately have the same optical thickness and equivalent refractive index such as a single layer. There are some equations that can theoretically calculate the optimum refractive index for single layer coatings and optimum thickness of the used materials in double layer coatings. However, there is a difference between simple calculations and the results of the good simulators. A useful research in ARCs can be investigating the real optimum refractive index and thickness that can significantly reduce the reflection.

In this paper, the effects of refractive index and thickness of the single and double layer antireflection coatings in GaAs single cell have been studied. The structure of a GaAs solar cell and the simulation results of the paper are presented in the next section. In this section the single and double layer antireflection coatings are studied. In section 3, the electrical and optical behavior of the single and double layer ARCs will be discussed.

2. Structure and Simulation Results

In this paper, a single junction GaAs solar cell with the single and double layer antireflection coating has been designed and simulated. The presented structure is shown in Fig. 1. The total area of the cell is 1cm^2 with 8% contact coverage on the front side. A 0.1µm $Al_{0.6}Ga_{0.4}As$ window layer is placed on the GaAs p-layer.

In general, the window layer allows electrons to flow to the contact without increasing the series resistance of the cell. Also, the back surface field (BSF) layer introduced at the bottom of the emitter layer decreases the dark current of cell and increases the open circuit voltage by reflecting the minority carriers.

Single and double layer antireflection coatings are used on top of the cell and the simulation results are accomplished under AM0 1sun irradiation; because the III-V solar cells are usually used in space applications.

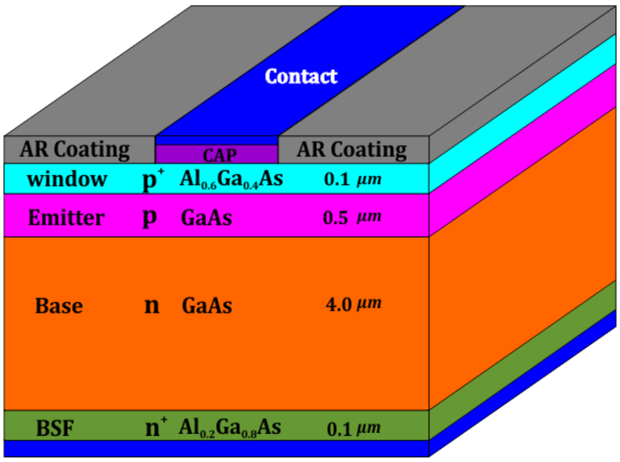

Fig. 1. Schematic of GaAs solar cell structure

2.1. Single Layer Antireflection Coating

The performance of the cell is evaluated for the single layer antireflection coatings with various refractive indices. Calculating the conversion efficiency and open circuit voltage for the different theoretical refractive indices of the used materials shows an ideal point for the cell. The solar cell power conversion efficiency is related to the incident light power, Pin, as follows:

$$\eta = \frac{P_m}{P_{in}} = \frac{V_{OC} I_{SC} FF}{P_{in}} \tag{1}$$

where P_m, I_{SC} and V_{OC} are the maximum output power, short circuit current and open circuit voltage, respectively. *FF* is the fill factor of the cell that is a symbol of squareness of the current – voltage (I –V) curve and can be calculated by:

$$FF = \frac{V_m I_m}{V_{OC} I_{SC}} \tag{2}$$

with V_m and I_m as the maximum voltage and current.

Figure 2 shows the curves of short circuit current, power conversion efficiency and open circuit voltage versus the variations of ARC refractive index.

The flux of photons is a maximum at around 650nm in the solar spectrum. Therefore, the coatings are usually designed to present the minimum reflection in 650nm. The ideal case for the single layer coating in Fig. 2 is happened in a refractive index equal to 1.88. The primary calculation about the best thickness for zero reflectance in a coating with n=1.88 gives 86nm thickness. It is obvious that an available material with the optimum index can significantly reduce the reflection of the incident light. It should be noted that the different points of refractive index shown in Fig. 2 are based on the theoretical calculations. Also, the materials of antireflection coatings should have some other properties such as the high energy band gap to reduce the absorption of the incident light. Therefore, this is hard to find a dielectric material with the ideal refractive index and high band gap energy to be applied as coating. Some materials that are commonly used as ARC in GaAs-based solar cells are pointed in Fig. 2.

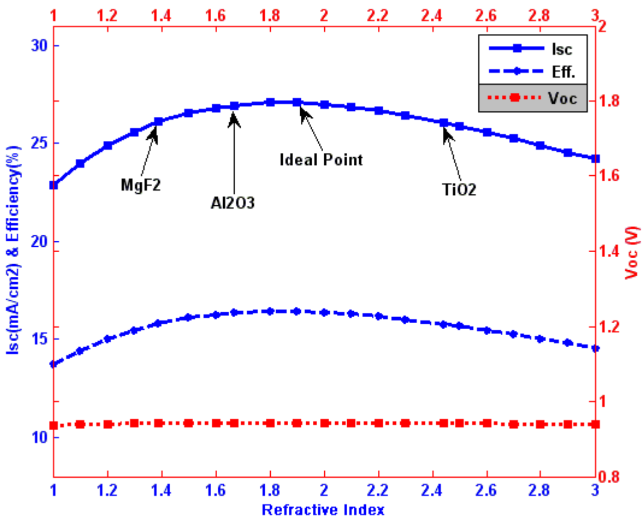

Fig. 2. The curves of short circuit current, power conversion efficiency and open circuit voltage versus the refractive index of antireflection coating

2.2. Double Layer Antireflection Coating

Double layer antireflection coatings reduce the reflection of the solar cell in a higher range of wavelengths. The projected view of the solar cell in Fig. 1 with double layer antireflection coating is shown in Fig. 3.

In order to design this structure, the refractive indices of the ARC layers can be theoretically calculated as follows [8]:

$$n_1^3 = n_0^2 n_w \quad , \quad n_2^3 = n_0 n_w^2 \tag{3}$$

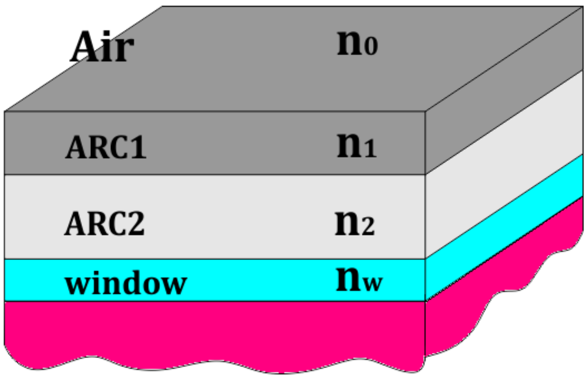

Fig. 3. Projected view of the antireflection layers

As mentioned before, the refractive indices of materials are calculated in 650nm wavelength due to the high photon flux of the solar spectrum. Using Eq. (3), the optimum refractive index of the ARC layers can be achieved n1=1.53 and n2=2.35.

The dielectrics such as Al_2O_3 and TiO_2 are the well-known antireflection coatings that have refractive indices near these optimum values. Therefore, we used a two layer Al_2O_3/TiO_2 coating in the structure. Total thickness of the double layer ARC has been chosen 86nm same as the previously calculated for the optimum single layer ARC. In order to achieve the optimum thickness percentage of mentioned materials, the thickness percentage of TiO_2 layer is studied and the efficiency of structure is calculated in various cases. Fig. 4 presents the changes of the short circuit current and conversion efficiency in the solar cell based on the variations of the TiO_2 thickness percentage in Al_2O_3/TiO_2 double layer ARC.

As can be understood from Fig. 4, the performance of the structure is increased with decreasing the TiO_2 thickness. Also, the higher percent of TiO_2 shows the better results in comparison with the middle percentages; Because TiO_2 enhances the absorption of the cell in the UV wavelength region. Although decreasing the thickness of the TiO_2 layer changes the behavior of the coating from double layer to single layer, but the simulation results show that a double layer TiO_2/Al_2O_3even with a thin layer of TiO_2 makes the improvements in comparison with Al_2O_3 single layer coatings.

From Fig. 4, we attained 16.97% as the maximum power conversion efficiency and 27.91mA short circuit current for 5nm TiO_2.

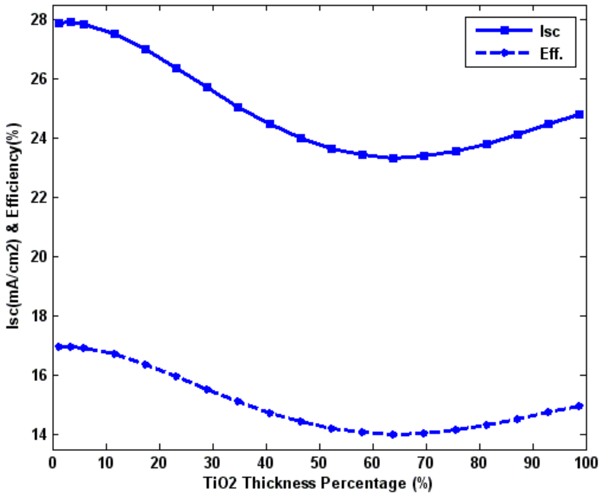

Fig. 4. Short circuit current and power conversion efficiency versus TiO_2 thickness percentage in Al_2O_3/TiO_2 coating

3. Discussion

Figures 2 and 4 give the optimum cases for single and double layer antireflection coatings, respectively. As mentioned, the double layer TiO_2 / $Al_2O_3$with a thin TiO_2 layer shows the better performance in comparison with Al_2O_3 single layer coatings. The comparison between the performance of the cell for single layer Al_2O_3 and TiO_2 coatings and Al_2O_3/TiO_2 double layer with the optimum thickness persuades us to work on multilayer coatings. The performance of the antireflection coatings can be carefully studied with the reflectance and external quantum efficiency (EQE). External quantum efficiency of a solar cell includes the effect of optical losses such as transmission and reflection. EQE is the ratio of the number of charge carriers collected by the solar cell to the number of incident photons. The reflectance and external quantum efficiency of the solar cell are shown in Figs. 5a and 5b, respectively. In this figure, the effects of antireflection coating on these parameters can be clearly observed. The cases of without and with single or double layer coatings have been simulated.

In the solar cells the high energy photons are absorbed near the front surface. Also, modifying the front surface of the solar cell can increase carriers that are generated near the surface. Therefore, the remarkable recombination at the front surface affects the left side of the EQE curve.

As can be seen in Fig. 5, there is a considerable improvement in the performance of the cell by using the antireflection coating in comparison with the case of ‘no ARC’. Also, the single layer Al_2O_3 or TiO_2 coating have the lower external quantum efficiency in comparison with the optimum double layer Al_2O_3/ TiO_2 coating. As discussed in the previous section, Al_2O_3 single layer presents more EQE than the TiO_2 ARC because of the nearness of its refractive index to the ideal refractive index of single layer antireflection coatings.

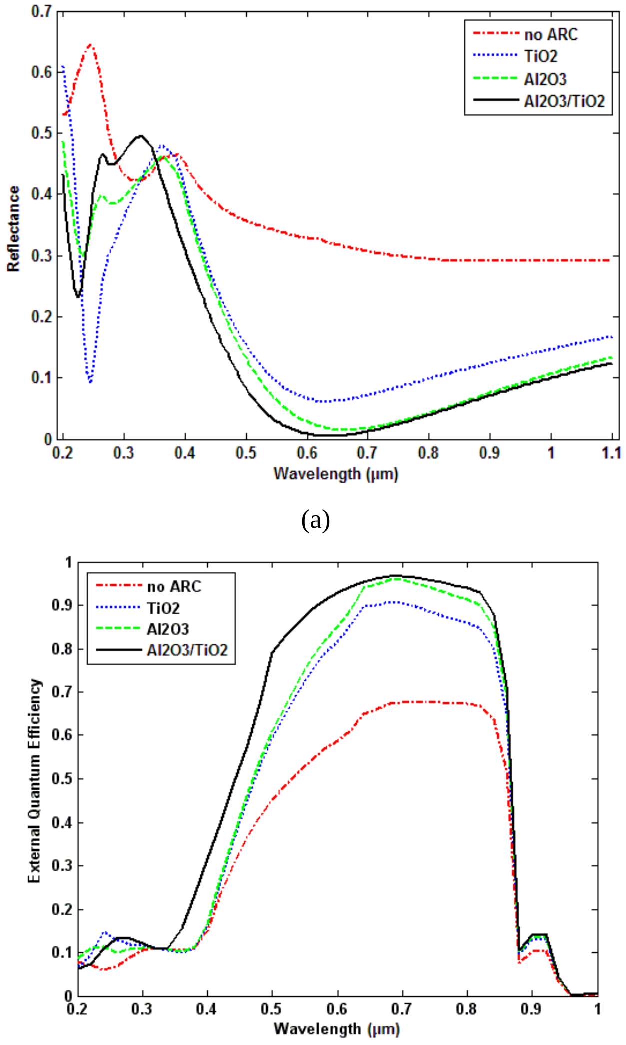

Fig. 5. (a) Reflectance and (b) external quantum efficiency of the proposed cell for different ARCs

Although the curves of single layer ARCs are pursuing the double layer coating in high wavelengths, but there is more difference between these curves in high energies. As explained, this difference is due to the front surface modification that is achieved with using double layer optimum antireflection coating. Also, as can be seen in Fig. 5a, the reflectance of TiO_2 ARC is less than the other structures in the UV wavelength region.

The current-voltage characteristic of the solar cell in the mentioned cases proves the behavior of the cell in Fig. 5. The highest short circuit current takes place in the optimum double layer coating. The I-V curves of the solar cell with and without antireflection coatings are presented in Fig. 6.

In Fig. 6, the I-V curve of the solar cell is compared for the cases of 'no ARC', 'Al_2O_3 single layer coating', 'TiO_2 single layer coating' and the optimum 'Al_2O_3/TiO_2 double layer coating'. The simulation results show that deploying double layer antireflection coating improves the I-V characteristics. According to Fig. 6, the structure of antireflection coating changes the short circuit current due to the increment of effective photon absorption of incident light while it has no effect on the open circuit voltage of the cell; because the open circuit voltage is usually varied with the thickness of the cell's active layers.

Short circuit current, open circuit voltage, fill factor and power conversion efficiency of the GaAs solar cell in the mentioned cases of ARC are presented in "Table 1". The double layer Al_2O_3/ TiO_2 ARC presents the better performance in comparison with its single layer counterparts.

Table 1. Cell characteristics with double layer, single layer and no ARC

AR Coating	Isc (mA/cm^2)	Voc (V)	FF (%)	η (%)
no ARC	20.2	0.9324	80.1	12.01
TiO_2	26.06	0.9416	80.77	15.78
Al_2O_3	26.95	0.9428	80.85	16.36
Al_2O_3/TiO_2	27.91	0.9439	80.89	16.97

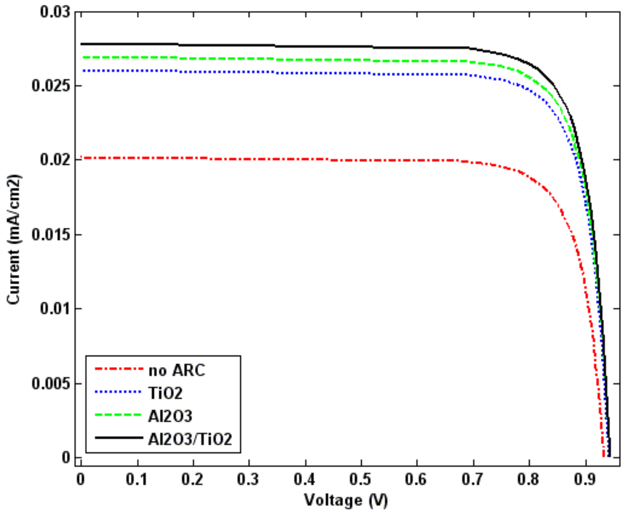

Fig. 6. I-V curves of the solar cell without and with one or two layer ARCs

Besides of previous discussions, the light incident angle affects the performance of the cell and changes the reflectance of the structure. Figure 7 shows the effect of incident angle on the reflectance of the cell with different cases of ARC.

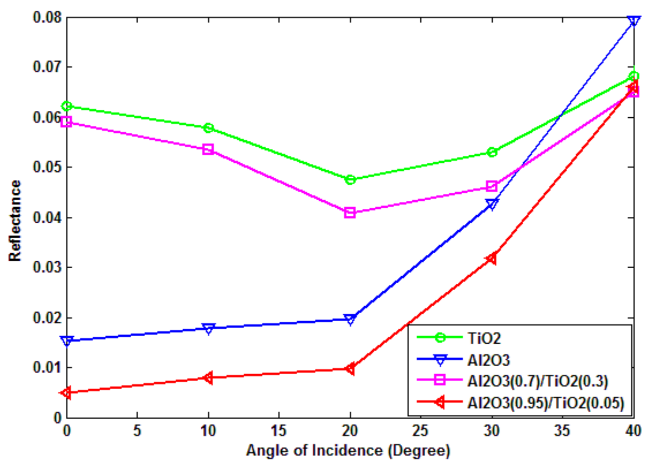

Fig. 7. The effect of incident angle on the reflectance of the cell

With comparing the Al_2O_3 and TiO_2 single layer ARCs, it can be noticed that TiO_2 single layer shows the lower variations of the reflectance with changing the angle of incidence. Therefore, although the double layer coating with the lower percentage of TiO_2 presents the lower reflectance, but the variations of the reflectance with changing the incident angle will be high. It can be managed with a tradeoff between the lower reflectance and lower angle dependency in order to achieve the optimum structure.

Finally, it should be noted that a comprehensive survey in order to find some materials with the exact optimum antireflecting properties can significantly reduce the reflection and absorption of the incident light. As mentioned before, these antireflecting properties contain the optimum refractive index to reduce the reflection and high energy band gap to reduce the absorption of the incident light.

4. Conclusion

In this paper, GaAs solar cell was investigated with different cases of single and double layer antireflection coatings. Single layer coatings show an ideal point that gives the maximum power conversion efficiency. The available materials with the refractive indices near the optimum case of single layer ARC can be Al_2O_3 and TiO_2. Therefore, the combination of these materials has been utilized as the double layer coating. Simulation results for the different thicknesses of them show an improvement for Al_2O_3/ TiO_2 double layer coatings with 5nm TiO_2 thickness in comparison with single layer coatings. Also, it has been deduced that the higher percentage of TiO_2 in double layer ARC decreases the dependency of the reflectance on the incident angle.

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