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Simulations of Antireflecting Coating on a Monocrystalline Silicon Solar Cell: Influence of Optical Parameters on a Double Layers

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Abstract The decrease in the reflection of light on the lens is due to the porosity of the surface on a very thin thickness due to the refractive index became lower at 30 %. It is well known that the deposition of one or more layers of certain materials on the front face of the photovoltaic cells and optoelectronic devices such as lasers, diodes, reduces the reflection of the incident light, which improves the performance of the cells. Solar energy, whose efficiency varies around 60 %. In this study, the influence of the thickness of an antireflection layer, in this case SiO_2, TiO_2, MgF_2, Si_3N_4, ZrO_2 on the spectral response of the solar cell to silicon which passes up to about 90 % for a layer of $MgF_2/TiO_2/Si$ whose refractive index values are respectively n = 1.3767 and n = 2.5742 quite far apart.

Keywords: *solar cell, antireflection coating, spectral response, thickness, refractive index*

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1. Introduction

The surface of semiconductors contains a high density of defects, resulting in significant losses related to surface recombination. Reflection losses around 30% for uncoated silicon also lead to a loss in spectral response. Thus an optimization of the solar cells by putting antireflection layers of refractive index and different thicknesses will be a good compromise to reduce the reflectivity on a flat surface of silicon under normal incidence [1].

The anti-reflective materials used in this study have an advantage because of their gradual indexes of refraction of the substrate towards the best environment. Magnesium fluoride (MgF_2) with refractive index and quarter-wave thickness (n=1.3767, e=118 nm) deposited on titanium oxide (n=2.5742, e=63 nm) gives a greater gain on the spectral response that ranges from 60 % over a range of 500 nm to 1000 nm (Figure 4, Figure 5).

However, in order to overcome a problem of having a greater gain in efficiency, the principle of antireflection must be respected, namely a destructive interference (Figure 1) at the reference wavelength (λref=650 nm) or notes a decrease in reflectivity for all materials except double layers that are less sensitive to solar radiation over the range of 500 nm to 900 nm, thus a zero reflectivity over a wide range of the spectrum is noted for materials whose indices refractions are quite distant and closer to the refractive index or antireflection $= \sqrt{(\text{nair} \times \text{nsilicon})}$ which is worth this study nAR = 1,9630 and that of unencapsulated silicon representing (n0=1) our solar cell is nSi=3.7640 (Figure 2, Figure 3). The variety of materials that can be used as anti-reflective coatings provides several solutions. Among these different materials, Magnesium fluoride (MgF_2), silicon nitride (Si_3N_4), Silicon Oxide (SiO_2), and TiO_2, have shown interesting properties by reducing the reflectivity to less 15% silicon that is 35% over the range of the solar spectrum. Simulations studies have shown the influence of antireflection layer thickness and the impact of stacking on cell performance as well as the spectral response of a conventional silicon p-n junction have allowed for a better understanding of the c is different approach of optimization of cells with antireflective coatings.

2. Calculs and Simulations

The different equations below make it possible to calculate the simulations on the parameters of the spectral response by taking into account the destructive interference of the physical phenomena on the air substrate interface [2].

$$\delta_j = \frac{4\pi n e_{arc}}{\lambda} = \pi \tag{1}$$

$$e = \frac{\lambda}{4n} \tag{2}$$

These two expressions represent the phase difference and the quarter-wave thickness ratio at destructive interference at normal incidence.

$$R = r.r^*, T = t.t^* \quad (3)$$

And these two expressions of reflection are deduced from the preceding expressions and are illustrated in the figure below:

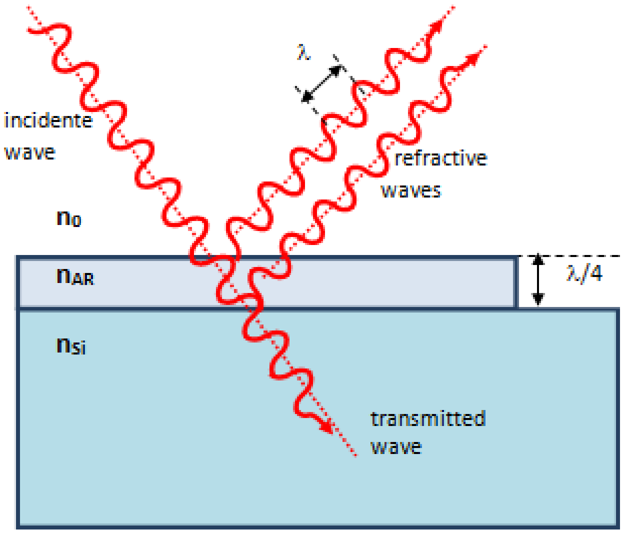

Figure 1. Principle antireflection interface

And for these different studies, the matrix product makes it possible to have the structure of several stacks on the flat surface of a monocrystalline silicon solar cell.

The expressions of the stacks and the crossing of the diopters are illustrated in the figure below (Figure 2) whose multi-level stacks are shown in the equations below, which make it possible to calculate the different light ray traverses within the cell whose amplitude of the incident wave is E_0 and of the transmitting wave equals Er where the ratio gives the simple reflection in intensity:

$$r = \frac{E_r}{E_0} \quad (4)$$

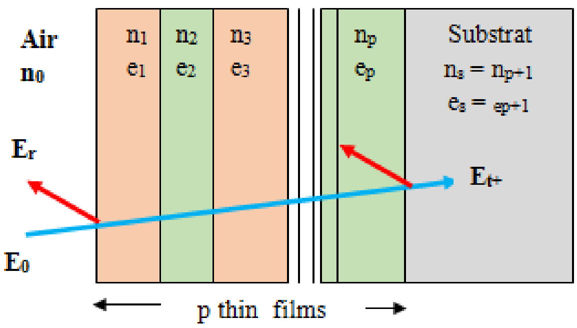

Figure 2. Structure of several stacks

The following expressions make it possible to determine the amplitude reflections for the different interface of the substrate towards the ambient environment:

$$\begin{pmatrix} E_r \\ E_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} E_t^- \\ E^+{}_t \end{pmatrix} = M \begin{pmatrix} E_t^- \\ E^+{}_t \end{pmatrix} \quad (5)$$

$$r = \frac{M_{12}}{M_{22}}; t = \frac{1}{M_{22}} \quad (6)$$

From these expressions we deduce the amplitude reflectivities seen previously. The matrix method is more generally on the optical calculations of the reflectivity and the transmission because of the fact that the different optical aspects namely the destructive interferences on the various interfaces (Figure 1) of which we can have a null reflectivity that from a reference wavelength at normal incidence [3,4]. These different studies will allow us to trace the different reflectivities of the materials mentioned above and deposited on a flat surface of monocrystalline silicon following various optoelectronic parameters related to the deposition on the surface of the silicon solar cell (The solar cell, used to simulate the spectral response, is an ideal p - n junction) whose parameters have the following values:

Thickness of silicon cell emitter: 0.5 µm; total thickness of the silicon cell: 200 µm; Doping transmitter (p area): Nd=1019 cm^{-3}; Doping of the base (zone n): Na=1016 cm^{-3}, Recombination rate on the front side Sp=0$cm.s^{-1}$, Recombination rate at the rear surface Sn=0$cm.s^{-1}$ (Back Surface Field). These different parameters used allowed us to draw the following different figures and whose values of the indices are represented in Table 1:

Table 1. Differents values of antireflecting coatings materials

Layer 1	**Materials**	**MgF_2**	**Si_3N_4**	**ZrO_2**
	Thickness	118 nm	80 nm	80 nm
	Indice	1,3767	2,0374	2,1494
Layer 2	**Materials**	**SiO_2**	**TiO_2**	**ZnS**
	Thickness	112 nm	63 nm	63 nm
	Indice	1,4565	2,5742	2,3450

And these different materials are taken with their optimal refractive index to respect the principle of antireflection (Figure 1). The figure below reflects the amplitude reflectivity of the different antireflection materials shown in Table 1. The computations of this simulation were established following the conditions of amplitude on the different interfaces at the reference wavelength λref = 650 nm.

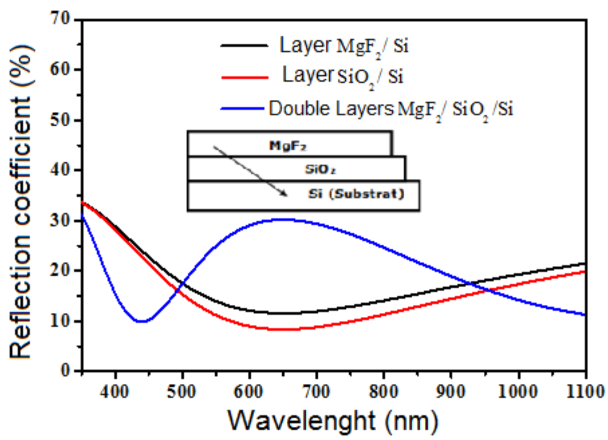

Figure 3. Coefficient de réflexion de monocouches de MgF_2 (indice 1.3767), de SiO_2 (1.4565) et d'une double couche MgF_2/SiO_2 sur substrat de silicium (nSi = 3.8515)

The Figure 2 shows a structure of a single antireflection layer on silicon ie the following materials (Table 1), she showed that for simple anti-reflective layers from 500 nm to 800 nm, more particularly in the visible spectrum band, a gradual decrease in the reflectivity of MgF_2/Si and SiO_2/Si, reflecting the sensitivity of the single layers to the beams of the incident photon flux within the cell at high energy. And on the same photon band the double layer MgF_2/SiO_2/Si its reflectivity and significant up to about 30 % at the reference wavelength whose value is more or less similar to the reflectivity a flat surface of silicon without anti-reflective coating. This structure shows the low penetration of the light-photon flux within the DCAR structure due to the fact that the indices of the two materials (Table 1) being rather far away affecting the respective thicknesses (equation 1) of the two materials because being proportional, The optical path of penetration of the light rays within the cell decreases, thus reducing the transmission and increasing the reflectivity. And beyond 900 nm towards the low energies higher than the silicon gab energy, the materials are no longer sensitive to the incident photon flux, hence a cancellation of the DARC (Double antireflecting coating) values and a stabilization of the reflectivity of the SCAR (simple antireflecting coating) towards the infrared domain. These different studies have allowed us to work on different DCAR structures to see the cancellation of its reflectivity in relation to different thicknesses and refractive index variables to have a decrease or even a cancellation of the reflectivity on a wide range of the visible spectrum. Thus, the representations in Figure 4 reflect the amplitude reflectivities of the different single and double materials for different values of the refractive indices crossing from the ambient medium to the substrate respectively of MgF_2/TiO_2/Si (Table 1).

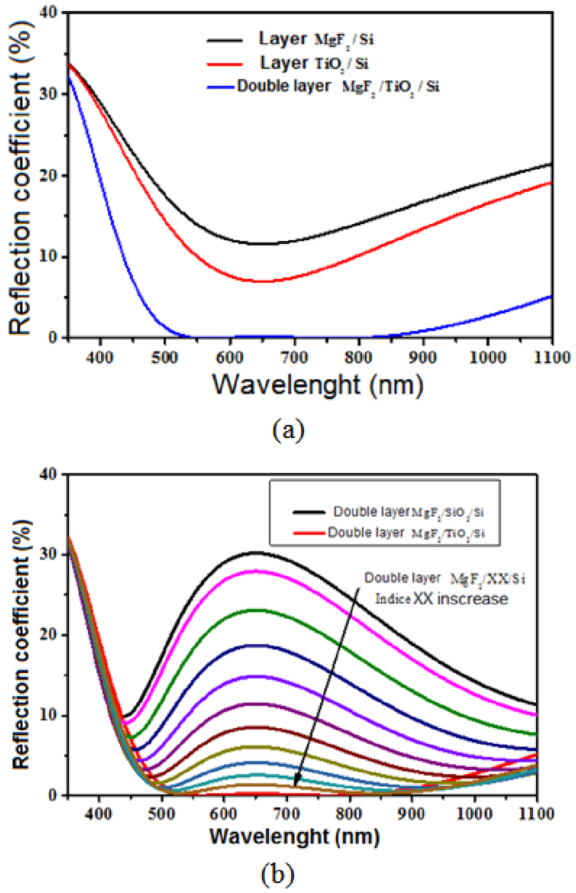

Figure 4. Reflectivity of the double layers MgF_2/TiO_2/Si (a) and reflectivity of a layer of MgF_2/X/Si with different values of the refraction index of material X (b)

The representation shows in Figure 4 a difference in reflectivity over the wavelength range between 500 nm and 800 nm. Indeed the results of Figure 4-a in the form of "V", illustrious of the reverse phenomena seen in (Figure 3), because here the double antireflection layer is more sensitive to the incident photon flux due to the refractive indices quite distant materials. Amplitude conditions being satisfied destructive interference resulting in a wide range of cancellation of the reflectivity on the visible spectrum from 550 nm to 850 nm. Thus to see the impact of these refractive indices between the materials used have to vary these different values. And Figure 4-b illustrates the variations of the different indices of the refractions increasing from MgF_2 towards a material X up to silicon, the basic materials of our coatings. The study showed that the inverted V structure has a lower reflectivity structure than for material X indexes closer to the substrate and farther away from the MgF_2 material closer to the environment. However, it is noted that the reflectivity is zero between 550 nm and 850 nm, a band comprising the reference wavelength. Thus, the comparison between a monolayer and a double layer leads to the conclusion that the simple coating is more sensitive to the reference wavelength than the double layer (inverted V and U). However, these studies allowed us to study the influence of materials on the quantum yields modeled on the different materials seen in Table 1, according to their refractive index and optimal thicknesses. The following figure illustrates a representation of the spectral response showing an improvement in the performance of different studies of antireflection materials on a monocrystalline silicon solar cell following a simple antireflection coating.

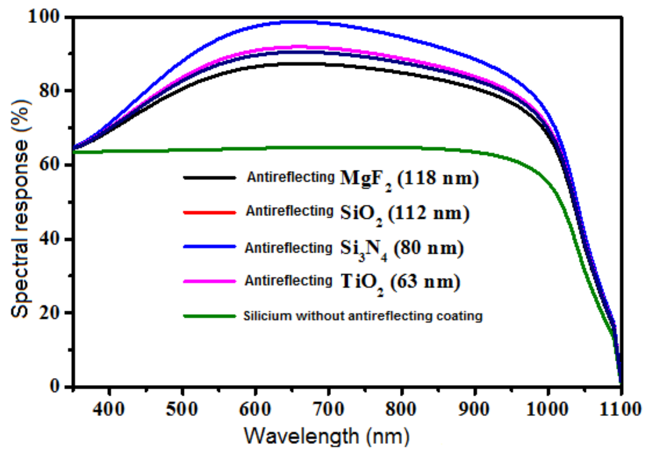

Figure 5. Spectral response of a simple antireflecting layer for differents materials on the silicon solar cell interface

The study carried out in Figure 5 allowed us to study the spectral response according to the visible spectrum of the different antireflection materials following their optimal index and thickness values calibrated at λref = 600 nm. In the wavelength band between 650 nm and 1100 nm, there is a gradual decrease in the spectral response which is explained by a very low absorption of the incident light with photon energies close to the silicon gap. Above 1100 nm, corresponding to photon energies below the gap of silicon, the spectral response vanishes. Of the materials used, Si_3N_4/Si has the best response compared to other coatings. The refractive index of Si_3N_4, which is 2.0374, is close to the optimal index related to the amplitude condition. In this a study on the study the spectral response is made on the silicon cell coated with two anti-reflective layers in Figure 6 below, the indices of the materials varying from the largest to the smallest starting from the substrate which is the silicon to the upper outer layer.

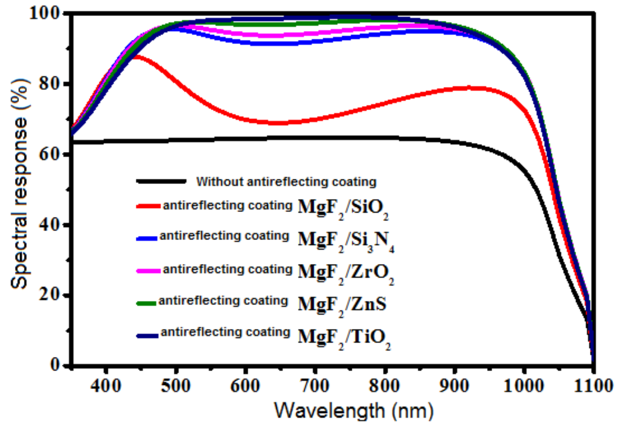

Figure 6. Spectral response of a silicon solar cell with various double layer coatings

This yield varies according to the materials used from 60 % to 95 % in the case of solar cells with double anti-reflective layers. The larger the thickness, the greater the probability that light radiation will be transmitted in the substrate and therefore the solar cell will produce higher spectral responses. Simulations were performed on various coatings composed of magnesium fluoride MgF_2 which has the smallest refractive index and which has been associated with other materials, giving the following structures: MgF_2/SiO_2, MgF_2/Si_3N_4, MgF_2/ZrO_2,

MgF_2/ZnS and MgF_2/TiO_2. Unlike cells with a single coating, those designed with a double layer show spectral responses greater than 85 % in a larger part of the 500 nm to 900 nm spectrum. The combination of two refractive index layers having a significant difference widens the spectral band with a good external quantum efficiency. This is the case of the association MgF_2/TiO_2 (with respective indices n=1.3767 and n=2.5742) which gives a better spectral response than the association MgF_2/SiO_2 (with respective indices n=1.3767 and n=1.4565). In addition, the MgF_2/TiO_2 structure has the advantage of depositing a lower layer of TiO_2 (63 nm) compared to that of SiO_2 (112 nm).

3. Conclusion

The Figure 2 and Figure 3 have shown us the importance of the variation of refractive indices from the environment to the substrate. This variation of the refractive indices shown an important contribution in the spectral response because Figure 4 and Figure 5 illustrate this because there is a net increase in the response values of 500 nm to 900 nm in the visible spectrum of the layers whose Refraction is further away from the creation of destructive interferences in the antireflection structure (Figure 1). In sum, the reflectivity has been attenuated by influencing the refractive index proportional to the thickness, which is equal to a quarter of the fixed wavelength, and especially as the widening of the thickness causes the maximum trapping of light in the solar cell decreased reflectivity and increased transmission influencing a large value of the spectral rest noted on this same range of the visible spectrum. Thus the materials namely MgF_2 and TiO_2 have the best possible structure for a double layer and a better reflectivity of Si_3N_4 for a simple structure because of its refractive index close to the refractive index ($n_{Optimal}$=1.9401). The studies thus carried out showed yields greater than 85 % for MgF_2/TiO_2 antireflection materials (difference in refractive indices and thicknesses quite appreciable) or the influence of the thicknesses and indices of refractions to the length of reference wave influence to attenuate the reflectivity down by 30 %. This made it possible to have an important spectral response for this type of coating. The optimization of silicon solar cells to increase the spectral response and to decrease the reflection in solar cells can take place by effecting a texturization within the monocrystalline silicon solar cell, which can generate a multitude of reflectivity of the light waves at the within the solar cell.

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