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Research Article

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Impact of Thickness, Refractive Index and Diffusion Length of Minority Carriers on Antireflection Materials: Study on the Spectral Response of a Monocrystalline Silicon Solar Cell

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Abstract In this work, the following materials were chosen as anti-reflective layer namely magnesium fluoride (MgF_2); silicon oxynitrides (SiO_xN_y), silicon oxides (SiO_x), silicon nitride (Si_3N_4) and hydrogenated silicon nitride (SiNx: H). The calculations were made on the basis of layer thickness values and refractive indexes which allow the phase and amplitude conditions to be respected. Numerical simulations have shown that weak reflectivities on the surface of the plane cell coated with a single layer can be obtained. For example, for simple coatings of materials based on Si_3N_4 and SiO_x, a value of the reflectivity is obtained rotating around 3 and 2% respectively. Structures with multilayer type coatings such as SiOx/SiNx:H / Si, give a very low reflectivity around 1%. Thus, the refraction index of the coating is an important parameter which plays a major role in the optical properties of the materials. The closer the refractive index is to the index of the substrate or the layer above the substrate, the greater reflectivity.

Keywords Antireflection layer, reflection, quantum efficiency, silicon, diffusion length

1. Introduction

These anti-reflective materials allow us to plot optical reflectivity and absorption against wavelengths and layer thicknesses. The refractive index and the optical thicknesses of the considered materials, which allowed us to have the lowest reflection, were used as a means to simulate the electrical properties of the cell. Thus, the results showed that the increase in cell efficiency by 0.3% and effective reflectivity by 7.4% is obtained with a first oxide layer ($n_1 = 1.5$ and $e_1 = 55$ nm), and a second nitride layer of silicon ($n_2 = 2.1$ and $e_2 = 53$ nm) compared to a reference solar cell (with single-shell sin-SCAR). In the case of a multilayer, our optimization unencapsulated has proved that it is possible to increase the efficiency by 0.7% with the refractive index [1]. The deposition of multilayer anti-reflection seems to be a good solution for reducing optical losses (the silicon surface reflects more than 30%). From this point of view, the appropriate materials considered physically and technologically are hydrogenated silicon nitride (SiNx: H), silicon oxynitride (SiOxNy), and silicon oxide (SiOx). They can be used as an anti-reflective cell because of their low absorption and adjustable optical properties and as a passivation layer. The refractive index n and the extinction coefficient of SiNx: H increase with the silicon content of the layer. So it can change from and to improve the transmission of fluxes of light photons within the solar cell.

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 1/2/3[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 parraport has a destructive interference at normal incidence.

$$R = r.r^{*} \qquad T = t.t^{*} \tag{3}$$

And these two expressions of reflection are deduced from the preceding expressions and are illustrated in the figure below [3]:

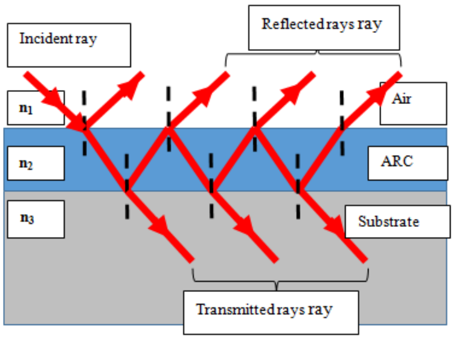


Figure 1: Principle antireflection interface

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 [4], [5]. 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:

$$r = \frac{E_r}{E_0} \tag{4}$$

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

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

$$r = \frac{M_{12}}{M_{22}}; t = \frac{1}{M_{22}} \tag{6}$$

3. Study on the spectral response of the solar cell: Influence of the thickness of antireflective materials

Optical parameters such as refractive indices and thicknesses contribute to a significant improvement of the reflectivity thus increasing the transmission [6] , which allows us to have a good compromise on the spectral rests of a monocrystalline silicon solar cell in order to to increase the quantum efficiency of different anti-reflective layer deposition. 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 $cm.s^{-1}$ (BSF).
The studies show a significant variation in the spectral response of MgF_2 / Si, Si_3N_4 / Si, SiNx: H / Si, SiOxNy / Si, SiOx / Si, HfO_2 / Si. The studies below show us a study of the spectral response of a silicon solar cell coated with an antireflection layer; the attached values of the antireflection materials are taken at optimal values at the reference wavelength.

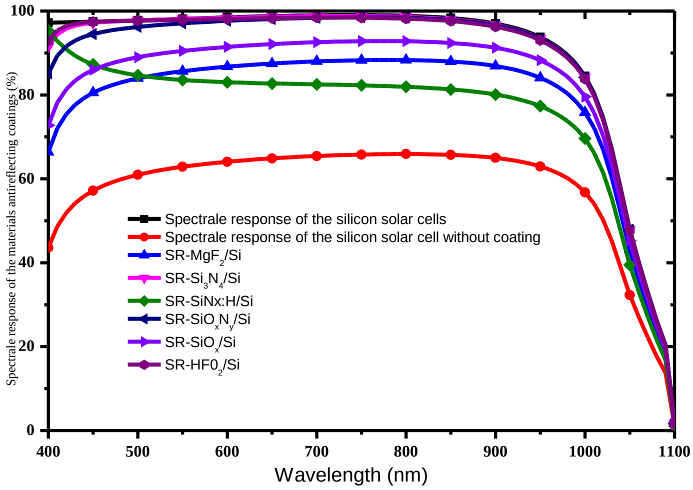


Figure 2: Silicon solar cell spectral response with different antireflection coatings

The optimal values of the materials are listed in Table 1, allowing a better understanding of the variations of the spectral response [7], [8].

Table 1: Variation of the refractive indices of the antireflection layers

Antireflecting Material	Wavelength	Refractive index
MgF_2	400 nm – 800 nm	1.3839 – 1.3751
SiO_2	400 nm – 800 nm	1.4701 – 1.4553
Al_2O_3	400 nm – 800 nm	1.7865 – 1.9127
ZnO	400 nm – 800 nm	2.1054 – 1.9591
TiO_2	400 nm – 800 nm	2.8717 – 2.5197
ZnS	400 nm – 800 nm	2.5434 – 2.3132
Si_3N_4	400 nm – 800 nm	2.1004 – 2.0242
ZrO_2	400 nm – 800 nm	2.0825 – 2.1494
Si	400 nm – 800 nm	5.5674 – 3.6941

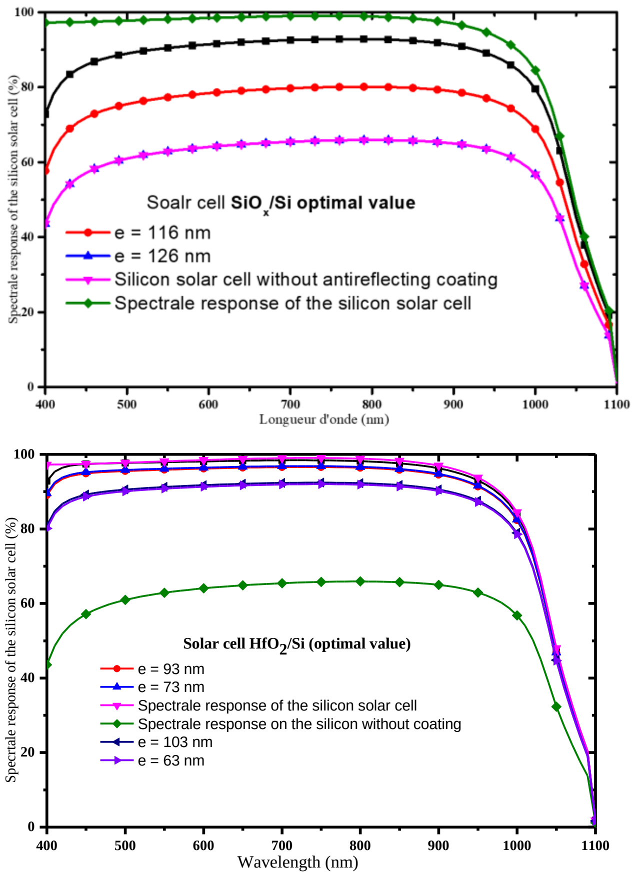
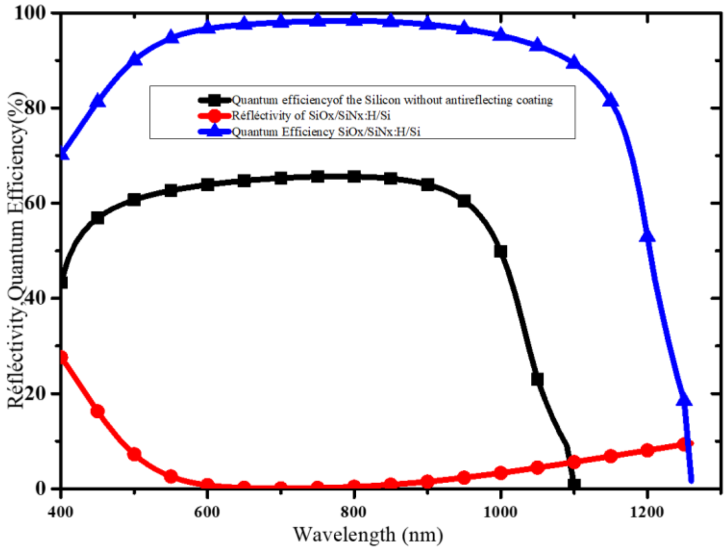


Figure 3: Spectral response of antireflection coatings for a single antireflective layer on silicon (SRAR), influence of optimal thicknesses as a function of wavelength

4. Study on the reflectivity of antireflective materials on the spectral response



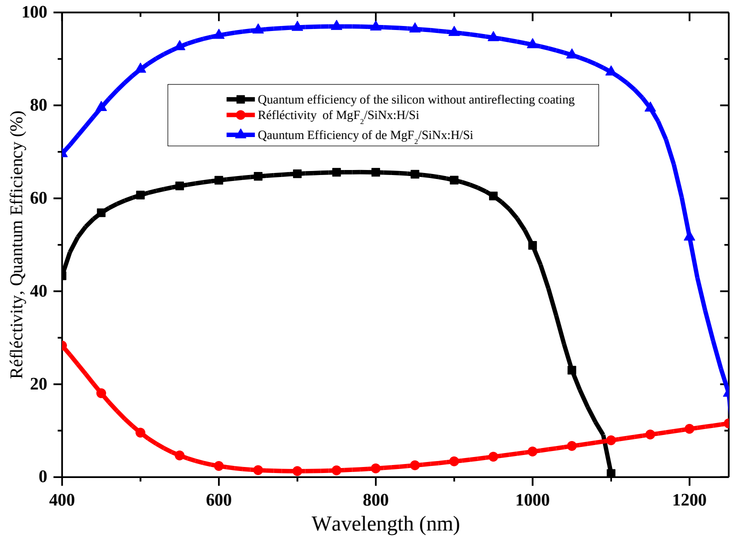


Figure 4: The reflection and quantum efficiency of antireflection coatings of silicon solar cells as a function of wavelength

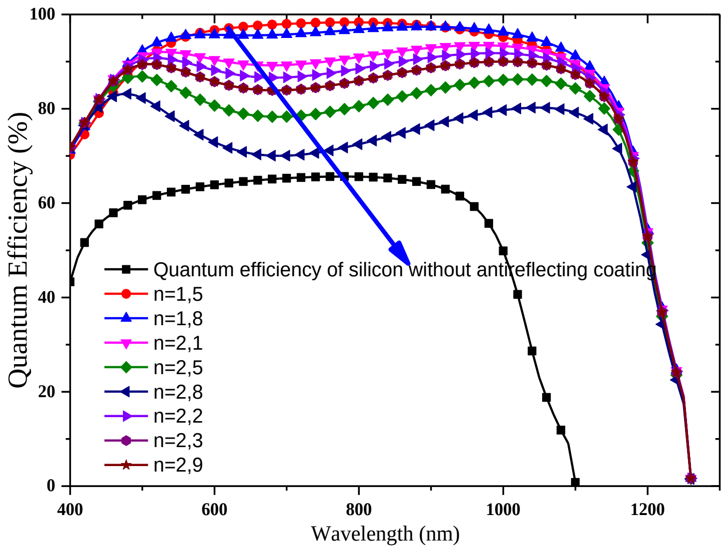


Figure 5: Influence of the refractive index values of antireflection coatings on the quantum efficiency silicon solar cells as a function of wavelength

In the wavelength band between 650 and 1000 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 lower than the silicon gap, the spectral response vanishes. The materials used, SiOx / Si has the best response compared to other coatings. The refractive index of SiOx, which is n = 1.5, is close to the optimal nair × nsilicon index linked to the amplitude condition. This explains the fact that the cell with SiOx antireflection layer has a spectral response of around 99% at the reference wavelength. On the other hand, it is observed that the response of the cell is lower in the range of the reference waveguide to an index of n = 2.8 which is quite close to the index of silicon, therefore different from the index optimal quoted above. The optimal thickness of the antireflection layer also plays an important role since it must be great for materials with a low refractive index which gives a relatively lower efficiency than those of the other materials mentioned above. The main challenge related to the performance of solar cells with anti-reflective coating is to find a sensible compromise in the choice of thickness and the targeted material to reduce manufacturing costs. However, a clearer increase in the spectral response shows an improvement in the generation rate of the minority carriers at the monocrystalline silicon solar cell.

5. Study on the reflectivity of a silicon solar cell Influence of the diffusion length (Lp) of the carriers on the solar cell

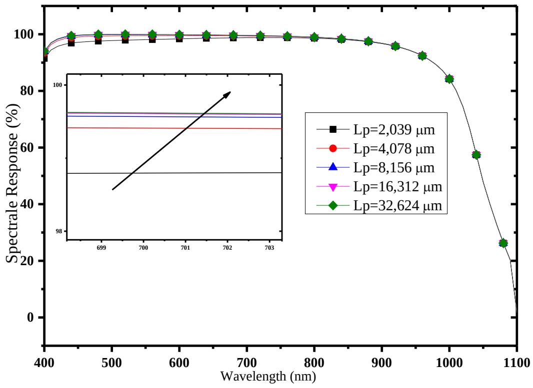


Figure 6-L: Influence of diffusion length (Lp) carriers on the solar cell spectral response depending on the wavelength

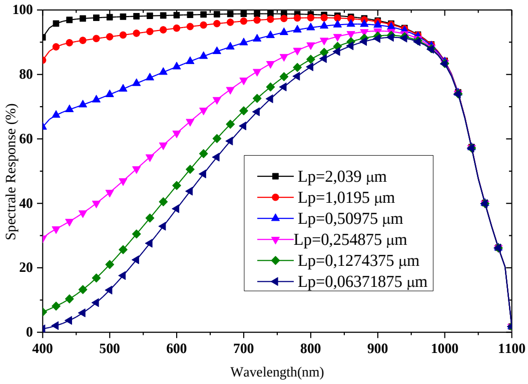


Figure 7-R: Influence of diffusion length (Lp) Bearers on the solar cell spectral response depending on the wavelength

In this figure 6-L we see that the curves have almost the same pace, hence the obligation to zoom in to see more clearly their difference. It is found that the longer the diffusion length increases the more the efficiency increases, and if one considers that the diffusion length is greater than or equal to the thickness of the base, almost all the carriers are collected, so this explains the uniformity at the level of the curve If the diffusion length of the photons is less than the thickness of the base for this graph we will successively divide by two the diffusion length of the carriers to see their behavior. However, figure 6-L shows a successive decrease in the efficiency, the more the diffusion length of the material decreases the more the quantum efficiency decreases and more and more there is a drop in the electron collection level. For diffusion lengths below the thickness of the base, it is considered that they have not reached the maximum length for collecting carriers, hence the drop in quantum efficiency, especially for diffusion lengths less than 700 nm.

6. Conclusion

Lastly, this work was devoted to simulating anti-glare layers such as and optimizing their performances. The analytic tools used to describe the models were first introduced. The parameters for evaluating the performance of an antireflection layer in a PV cell were then defined. The rest was focused on optimization. We have found that the performance of a double layer is slightly better than that of a single layer. A reduction of 0.3% in the reflection of the silicon surface was obtained. Silicon-antireflective multilayers have shown that this combination significantly reduces the reflection of the substrate surface and provides a current gain of more than 2.2 mA / cm^2 (5.5%) over to a PV cell with a single layer of Si_3N_4. However, the dispersion of the optical constants of SiNX and SiNx: H in the visible wavelength range of 400-800 nm must be taken into account and a compromise must be found between a high refractive index and strong absorption. Since these SiNX: H and SiOx layer optical constants increase with their silicon content, the deposition parameters must therefore be controlled so that this silicon content is not high. And the values on the quantum efficiency is close to 99% for conductive transparent type coatings or also a low value of the reflection coefficient is found around 2% at the reference wavelength corresponding to destructive interference at this point value limit.

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