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# Influence of the Refraction Index, The Thickness of the Antireflection Layer, The Spectral Response and The Texturization of a Silicon Solar Cell: Application to Antireflective Multilayers

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**ABSTRACT**
The optical losses correspond to the photons reflected on the front face and to those transmitted through the cell without being absorbed, whereas they could have generated electron / hole pairs. So to make the choice one must look for the relation between the refractive indices and the air give by the relation, the antireflection layer and the silicon allowing to have a reflectivity of 30% to 02% for a surface textured with the anti-reflective materials ($MgF_2$, $Al_2O_3$ and $Ta_2O_5$) Surface texturing is a technique of "coupling" light inside a PV cell by a multiple rebound effect resulting from internal reflection. It is used to decrease the reflectivity of the surface of the cell. With surface texturization the quantum yield against the variation of the refractive indices and the optimal thickness at the reference wavelength increases the latter from 60% to 98% for the materials listed below. The coating of a single X / Si type antireflection coating shows a greater importance of 99% efficiency for X = $Ta_2O_5$, to optimum refractive index close to the index of the antireflective layer, which is adequate to create a destructive interference at the reference wavelength.

**Key words:** Texturization, refractive index, thickness, spectral response, reflection

## INTRODUCTION

With the aid of the different antireflection materials $Ta_2O_5$, $Al_2O_3$ and $MgF_2$ (Table 1) we have plotted the characteristics of the reflection and the external quantum yield as a function of the wavelength calibrated at 600 nm on different materials used namely the $MgF_2$, Sapphire and $Ta_2O_5$. These features allowed us to make a comparative study of the two types of coatings namely texturized or plane on the silicon substrate (bare cell and that coated with a layer or double antireflection). Thus we have retained that the antireflection layer as well as the texturization makes it possible to increase the spectral response and that its index of refraction must be mastered to obtain this good answer [1,2,3]. Indeed this contribution that we have made on anti-reflective layers in silicon solar cells opens new perspectives taken into account and allowed us to show that the yield can go from 63% for bare silicon to 93% for a 98% antireflection coating for surface texturing monocrystalline silicon calibrated at 600 nm reference wavelength.

## MATERIALS AND METHODS

First, the development of the last two sections is briefly repeated for a general case of any layer.
The angle of the incident ray on a flat surface is between 0 and 65 °.

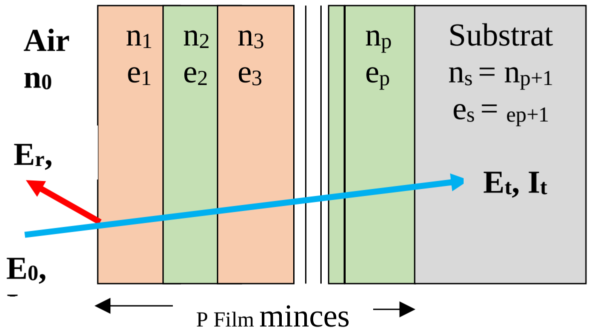


**Fig. 1** A thin film structure covering an active substrate for solar cells

The total amplitude Er of the reflected radiation and of the emission by the different layers is the product of all the amplitudes of radiation passing through the layers and the diopters separating two layers [4, 5].

$$\left(E^{-};0;E^{+};0\right) = \left(M_{11};\ M_{12};M_{21};M_{22}\right)\left(a^{-};s;a^{+};t\right) = M\left(E^{-};s;E^{+};t\right) \qquad (1)$$

The matrix M can be rewritten as such:

$$M = D_0.C_1.D_1.C_2\ldots.C_p.D_p \qquad (2)$$

The quantities Di are the matrix associated with the two layers i and i + 1:

$$D_i = \begin{pmatrix} \frac{n_i + n_{i+1}}{2n_i} & \frac{n_i - n_{i+1}}{2n_i} \\ \frac{n_i - n_{i+1}}{2n_i} & \frac{n_i + n_{i+1}}{2n_i} \end{pmatrix} \qquad (3)$$

The path difference between the two layers is given by:

$$C_i = \begin{pmatrix} e^{-jj_i} & 0 \\ 0 & e^{jj_i} \end{pmatrix} \qquad (4)$$

$$jj = \frac{2\ p\ n_i\ e_i}{l} \qquad (5)$$

The reflection and amplitude transmission coefficients are given by:

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

Those who are in intensity are:

$$R = r.\ r^{*} \qquad T = t.\ t^{*} \qquad (7)$$

## RESULTS AND DISCUSSION

### Study on a simple antireflection coating on a flat surface of monocrystalline silicon

The silicon photovoltaic cell is directly exposed to air (n0 = 1) at normal incidence and coated with an antireflection coating. However, the various antireflection materials used on this work are illustrated in Table 1 below, the index values and optimal thicknesses are at the referenced wavelength calibrated at 600 nm to create a destructive interference in the spectrum domain. Visible [6, 7, 8].

**Table -1 The values of the different anti-reflective materials**

| Materials (λréf=600 nm) | $MgF_2$ | $Ta_2O_5$ | $Al_2O_3$ | Si |
|---|---|---|---|---|
| Refractive index (n) | 1,3775 | 2,1276 | 1,764 | 3,9485 |
| Thickness (e) nm | 109 | 71 | 84 | 37,989 |

for which the phase condition is respected, the refractive index of the silicon is taken equal to 3.9485, the reflection coefficient is calculated for thicknesses of the $MgF_2$, $Ta_2O_5$ and $Al_2O_3$ layer equal to 109 nm, 71 nm and 84 nm, respectively. λ= 600 nm, figure. 2 represents the reflection coefficient of a $MgF_2$ / Si, $Ta_2O_5$ / Si, $Al_2O_3$/Si coating as a function of the wavelength for different optimal thicknesses of the layer [9, 10, 11, 12]. The calculations are made on the basis of the reference wavelength λ=600 nm.

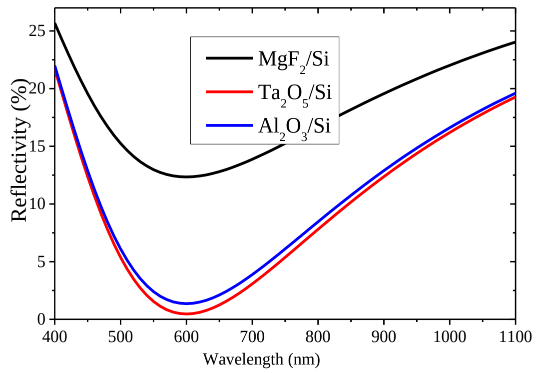


**Fig. 2** Coefficient of reflection of silicon coated with an anti-reflective layer of $MgF_2$, $Al_2O_3$, $Ta_2O_5$: Influence of the thickness of the coating for different wavelengths

The following structure shows three reflectivity propagation steps in the 400 nm-500 nm range where tantalum oxide has a lower reflectivity than sapphire and magnesium fluoride or lower light absorption. At the reference wavelength we note the lowest reflectivity namely (12.3% for $MgF_2$, 1.37% for sapphire and 0.42% for $Ta_2O_5$) for all anti-reflective materials studied explained. the fact that the materials are more absorbent and the transmission is favored, hence the reflectivities increases in increasing ways showing that the lower reflectivity threshold of these materials has been reached[13].

**Effect of thicknesses on the coating**

The layer thickness of the anti-reflective materials plays an important role in the optical properties. To study the influence of the thickness of the $MgF_2$, $Ta_2O_5$ and $Al_2O_3$ layers on the optical properties of the ARC (antireflecting coting)/Si heterojunction, the reflection coefficient is calculated according to quarter-wave thickness values. Figures 3-L, 3-R and 4 reflect this effect on reflectivity of minus 35% over the entire visible spectrum for all the materials shown below.

It has already been observed in the preceding sections that beyond the critical wavelength, the reflection coefficient decreases as the antireflection layer becomes thinner. The same phenomenon is observed here and it shows that the transmission of the luminous flux within the silicon increases when the thickness increases, which is explained by the elongation of the optical path of the luminous flux in the antireflection layer which favors its absorption. and attenuates reflection.

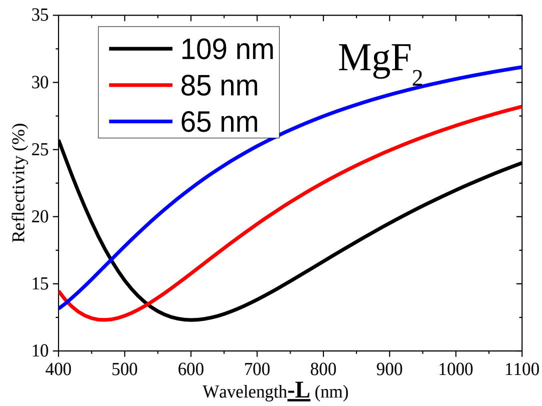


**Fig. 3-L** Coefficient of reflection of silicon coated with an anti-reflective layer of $MgF_2$. Influence of coating thickness for different wavelengths.

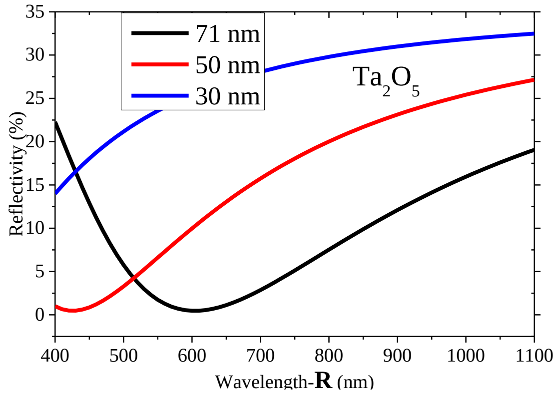


**Fig. 3-R** Coefficient of reflection of silicon coated with an anti-reflective layer of $Ta_2O_5$. Influence of coating thickness for different wavelengths.

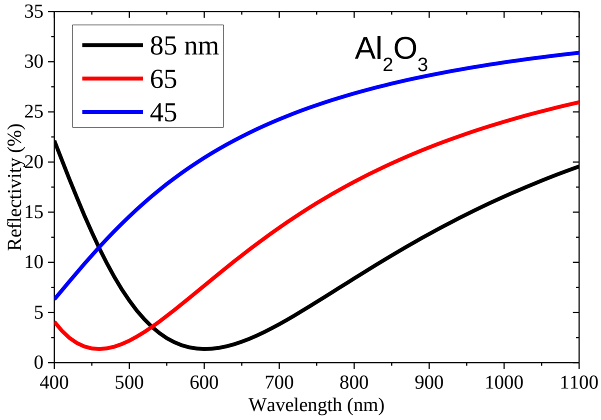


**Fig. 4** Coefficient of reflection of silicon coated with an anti-reflective layer of $Al_2O_3$. Influence of coating thickness for different wavelengths.

**Study on antireflective multilayers on a flat surface of monocrystalline silicon**
**Anti-reflective double layer**

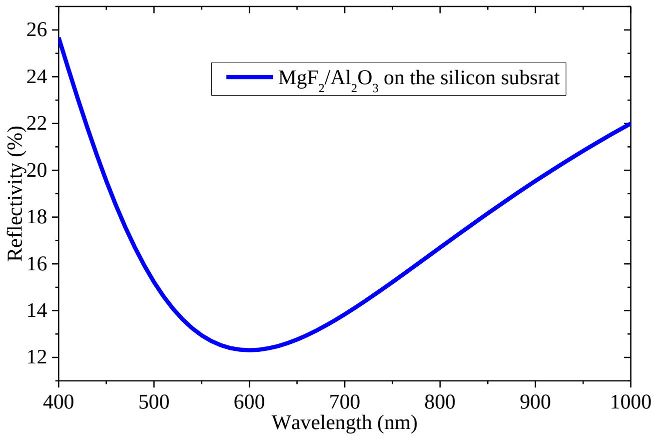


**Fig. 5** Coefficient of reflection of a double layer $MgF_2$ / $Al_2O_3$ on a silicon substrate (nSi = 3.9485).

This figure shows the configuration of a double antireflection layer combining the following materials: $MgF_2$ (n = 1.3775, e = 109 nm), and $Al_2O_3$ (n = 1.764, e = 85 nm).
A reduction in the reflection coefficient from low wavelengths is observed to become practically constant for a value of 12.34% at the reference wavelength calibrated at 600 nm, at the large energies of the incident photons. At long wavelengths the reflectivity on the flat surface of silicon of refractive index (n = 3, 9485) is important at low energy. This results in the fact that the silicon absorption threshold has been reached at low energy. Figure 6 below shows an antireflection double layer structure whose materials are: $Ta_2O_5$ (n = 2.1296, e = 71 nm) and $Al_2O_3$ illustrated above.

It is found that for a range of visible wavelength between 400 and 600 nm the same analysis as previously in Figure 4, the reflection coefficient is 02% where it becomes increasing to 1000 nm. It is also noted that the two reflection coefficients are practically identical in the long wavelength range of the visible range between 22% ($MgF_2/Al_2O_3$) and 20% for $Al_2O_3/Ta_2O_5$. On the other hand, we note the interest of the antireflection layer which reduces by 35% to 1.39%, the reflection coefficient of silicon in the range of long wavelengths.

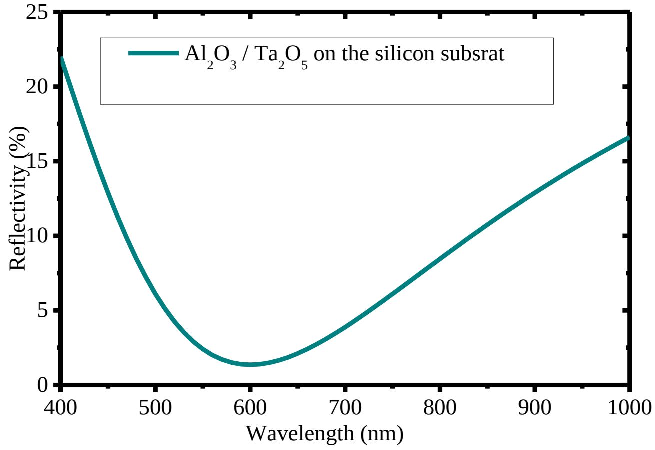


**Fig. 6** Coefficient of reflection of a double layer $Al_2O_3$ / $Ta_2O_5$ on a silicon substrate (nSi = 3,9485).

Study on texturing

The accompanying drawings show a flat, texturized structure on the surface of monocrystalline silicon having a refractive index equal to n = 3.9485 at 600 nm.

In this part, the simulation is done on the reflectivity of the silicon in the case where the front face is texturized and then in the case where this face is covered with an antireflection coating with materials such as $MgF_2$, $Ta_2O_5$ and $Al_2O_3$.

The attenuation of the incident luminous flux, before its transmission in the cell, is due to the flux of photons reflected by the front surface of the cell. The reflection coefficient is then close to 35% for optical monocrystalline silicon.

The figures 7, 8 and 9 show a silicon cell whose front face is textured to allow better trapping of incident light flux. In some situations, the texturization can ensure passivation of the semiconductor surface by eliminating certain pendant bonds at the surface of the silicon. In addition, the path of the ray transmitted in the cell increases within the silicon compared to the case of a flat surface; the probability of absorption of photons is improved.

The table below reflects the different values noted in the 3 representations illustrating that sapphire and $Ta_2O_5$ represent structures of lower reflectivity at the reference wavelength 600 nm.

**Table -2 The different values on materials textured the surface of monocrystalline silicon**

| | **$MgF_2$** | **$Al_2O_3$** | **$Ta_2O_5$** |
|---|---|---|---|
| Flat surface | 11,23% | 3,25 % | 1,43 % |
| Textured surface | 5,32% | 1,75 % | 0,45 % |

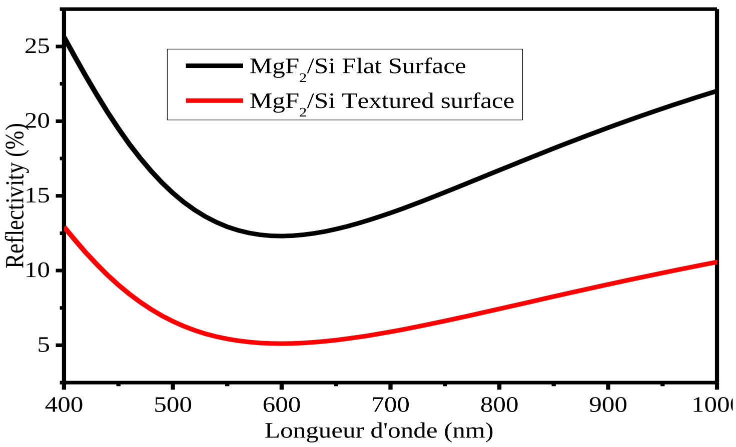


**Fig. 7** Coefficient of reflection of a $MgF_2$ / Si layer on silicon substrate (nSi = 3, 9485) flat and textured.

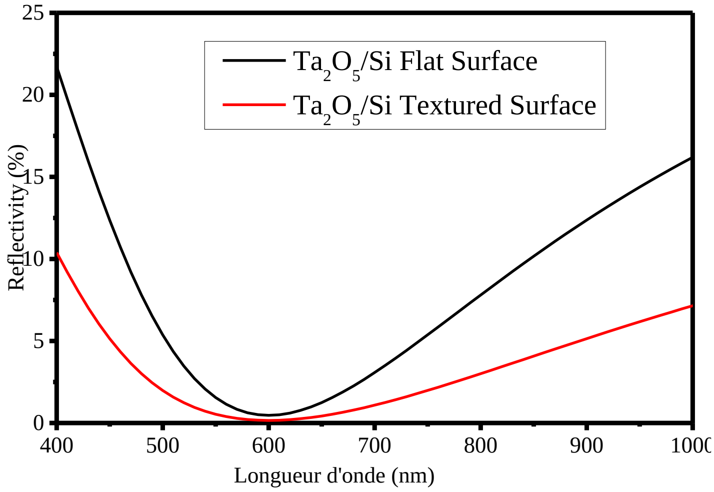


**Fig. 8** Coefficient of reflection a $Ta_2O_5$ / Si layer on a silicon substrate

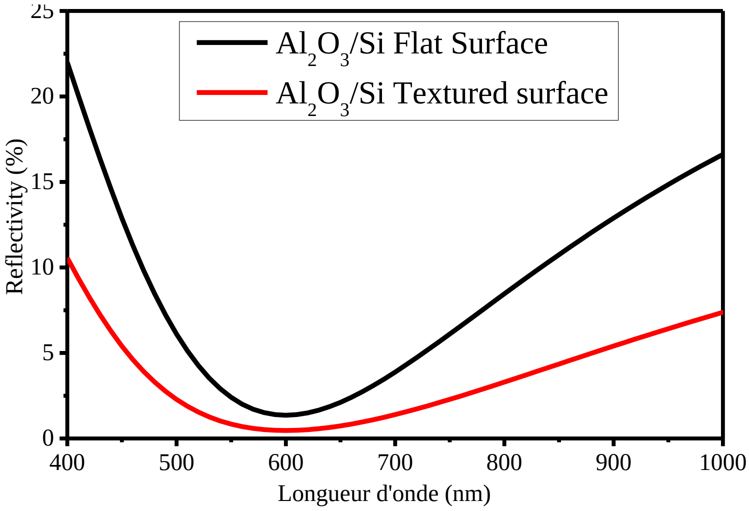


**Fig. 9** Coefficient of reflection of a $Al_2O3$ / Si layer on substrate

**Study on the spectral response of antireflection coatings on a flat surface**
**Influence of anti-coating materials.**

These curves show the evolution of the external quantum efficiency (or spectral response) of bare silicon and silicon coated with antireflection layers as a function of the wavelength of the materials. They are obtained by considering a reference wavelength of 600 nm and the indices of the materials as well as their optimal thicknesses. The analysis reveals two parts: For a range of wavelength between 400 and 850 nm, it is noted that the external quantum efficiency increases for bare silicon and for that with antireflection layer14. This increase is explained by the fact that in this wavelength range of the solar spectrum (400 to 800 nm, visible spectrum), the material is more absorbing (the energy of the incident photons is greater than the silicon gap) The answer is more important for the cell with antireflection layer, because there is a minimum of reflection caused by the deposition of a silicon layer. For a wavelength range of between 850 and 1100 nm for the visible range, there is a rapid and progressive 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. We also note that for long wavelengths corresponding to photon energies lower than the silicon gap, the spectral response vanishes. However, it is noted that the yield of the silicon coated with the anti-glare layers is much greater than that without coating. Among the materials used, tantalum oxide ($Ta_2O_5$) has the best efficiency at the reference wavelength 600 nm illustrated in the table below.

**Table -3 Different values on the spectral response of antireflection materials calibrated at 600nm**

| Values of the Special Response at 600 nm | **$Ta_2O_5$** | **$Al_2O_3$** | **$MgF_2$** |
|---|---|---|---|
| | 98,13 % | 97,00 % | 86,80 % |

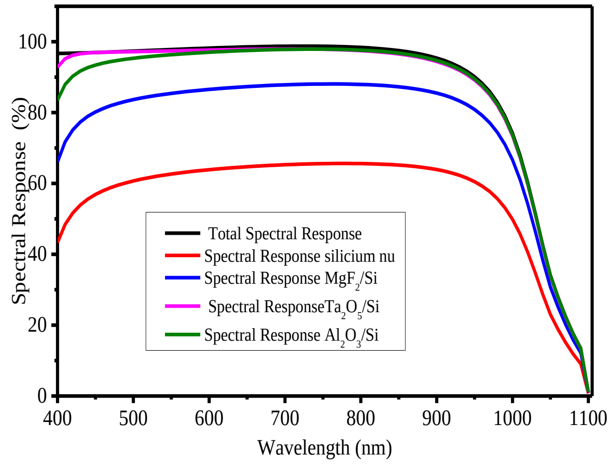


**Fig. 10** Spectral response of a silicon solar cell: influence of materials.

Influence of the thickness

The spectral response, and more particularly the external quantum efficiency, makes it possible to determine the response of the cell as a function of wavelength and makes it possible to study the factors limiting the performance of a monocrystalline silicon solar cell. Without antireflection layer, with the strong reflection on the surface of the emitter, the spectral response does not exceed 65% for the naked silicum. The antireflection layer improves this response with a maximum of around 90% for the reference wavelength as illustrated above. This maximum moves towards the long wavelengths as the thickness increases. For thicknesses less than 70 nm, the response increases at a wavelength below 600 nm, if the thickness decreases. The opposite effect is noted for thicknesses greater than 70 nm in the wavelength range greater than 600 nm. Thus, the optimal parameters of the reference wavelength and the quarter-wave thickness seem to govern the influence of the antireflection layer thickness on the external quantum efficiency of the solar cell. The decay of the spectral response at long wavelengths when the thickness of the AR layer decreases can be explained by the fact that the optical path of the luminous flux in the layer decreases, which does not favor the transmission in the cell and consequently the fall of the spectral response. The performances of the cell are then altered for the long wavelengths which are active only in the base of the cell. ref = 600 nm.λAnd these different findings are illustrated in Figures 11, 12-L and 12-R below represent the spectral responses of solar cells with a single anti-reflective layer namely MgF2 / Si, Ta2O5 / Si and Al2O3 / Si including the studies are calibrated at 600 nm15.

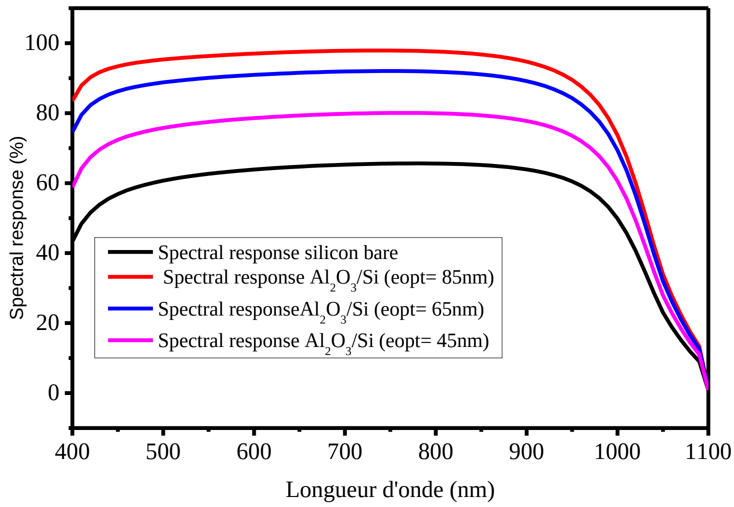


**Fig. 11** Spectral response of a silicon solar cell: influence of the thickness on MgF2 antireflection layer.

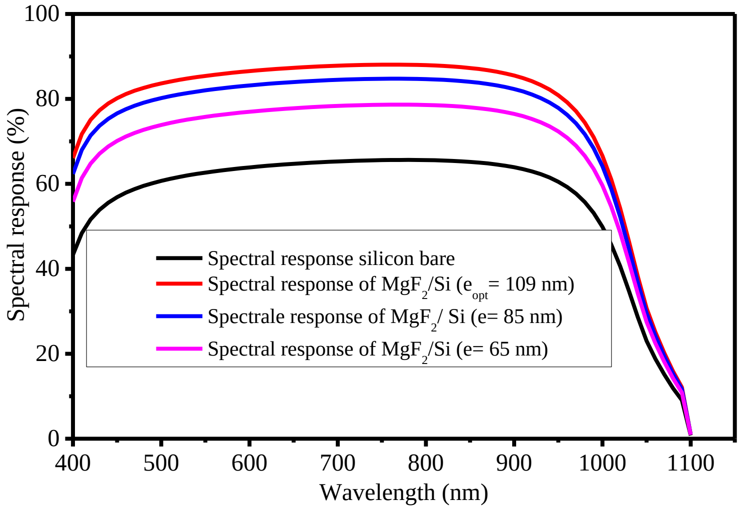


**Fig. 12-a** Spectral response of a silicon solar cell: influence of the thickness of a $Al_2O_3$ antireflection layer

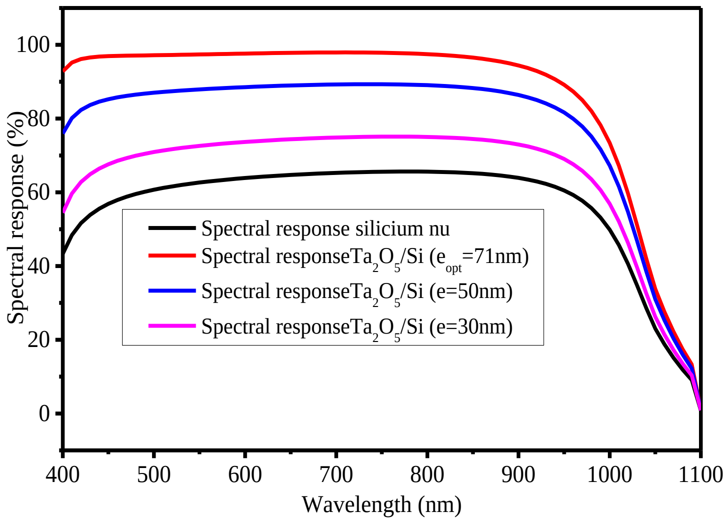


**Fig. 12.b** Spectral response of a silicon solar cell: influence of the thickness of a Ta2O5 antireflection layer.

Influence of the texturization of antireflection materials on the spectral response of monocrystalline silicon
The figures show the importance of the texturization of the monocrystalline silicon surface on the external quantum yield of the solar cell. This yield varies depending on the materials used. We have an external quantum yield that goes from 63% for bare silicon to 93.22% for MgF2, 97.84% for sapphire ($Al_2O_3$) and 98.63% for $Ta_2O_5$, cells without anti-reflective layers at 95%. % in the case of solar cells with antireflection layers. On the other hand, the influence of the refractive indices and optimal thicknesses of the materials on the spectral response is clearly visible on (Figures. 11 and 12). An increase in external quantum yield at long wavelengths is observed in the visible range between 600 nm and 950 nm.

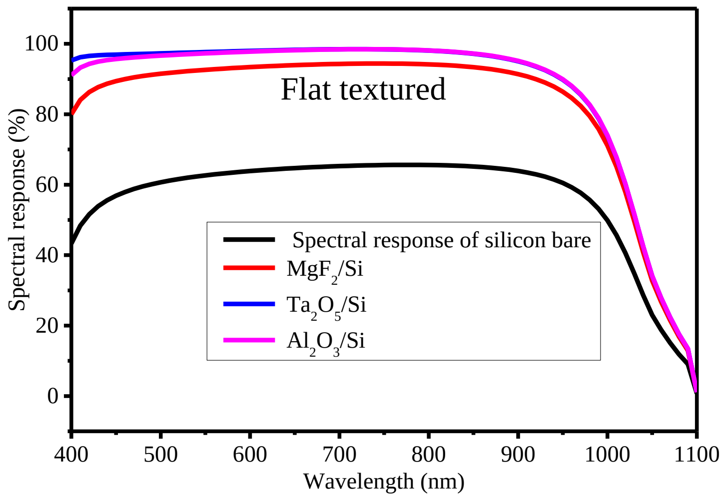


**Fig. 13** Spectral response of the silicon solar cell on different antireflecting materials

This figure shows the importance of anti-reflective layers and texturization on the reflection of silicon. This reflection varies according to the materials used of the type of coating and their indices of refactions and optimal thicknesses which influence the good quantum yield of the cells. It should be noted that for the materials used Ta2O5 presents a good compromise for a lower reflectivity and a quantum yield of the most important on the different types of processes used in this work.

## CONCLUSION

In this work we presented a theoretical study of the reflection and the anti-reflective layer. During this study we presented different types of silicon and their optical properties (reflection, transmission), starting from the study of the solar cell and of its different parts (base, emitter, space charge zone) we have established equations that allowed us to determine the electrical parameters such as the density of minority carriers, the current photo and the external quantum efficiency in these different parts. We have also seen that it was possible to reduce the reflection factor by 30% for a solar cell containing silicon to about 2% for a cell coated with a double antireflection layer at the reference length equal to 700 nm. Different approaches have been proposed: The deposition of one or more homogeneous layers on the surface of the silicon, the deposition of a layer or the index of refraction varies with the thickness and the use of the technique of texturing. The textured surface reduces reflectivity to one third of its value at the reference wavelength and thus increases the spectral response from 60% to about 98% for a textured surface. Multilayer deposition appears to be a good compromise for reducing the reflectivity of light rays on the unencapsulated surface of the solar cell.

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