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# The Equations and Optical Parameters of Antireflective Multilayers: A Literature Review

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## ABSTRACT

In this paper, the study is focused on the anti-reflection coatings on silicon solar cells and monocrystalline solar cells. The impact of optical parameters such as refractive index on the reflectivity as well as the impact of the as well as the impact of the diffusion length of the carriers was studied. The calculations performed according to the transfer matrices on the stacking of layers through the diopters have allowed establishing simulations for antireflective multilayer coatings. In our study, the reference wavelength was chosen equal to l= 700 nm, which gives us an optimal refractive index of silicon (n = 3.7838) corresponding to a reflectivity at the surface of 33%. To reduce this high reflectivity, the coating of the surface is a technique used to improve the transmission of the incident luminous flux in the active material and light flux in the active material which is silicon.

**Keywords**: Anti-reflective coating, single layer, multi-layer, reflection, refractive index

## Introduction

The first experimental observation of the anti-reflection effect was made in 1887 [1], and the application of anti-reflection layers to solar cells is relatively recent. It started with the use of photovoltaic energy by the space industry in the 1960s [2]. It is well established that reflection losses at the surface of a material can be significantly reduced by the application of a thin, transparent layer with a suitable refractive index and thickness called an anti-reflection layer. In this paper, we will detail how the optical properties of the layers are exploited to reduce reflectivity at the surface of photovoltaic cells.

## Anti-reflecting coating

The aim here is to exploit the phenomena of interference by amplitude division resulting from the introduction of a thin layer of dielectric material between the external medium (of index $n_0$) and the substrate (silicon of index ns). As illustrated in Fig.1, the choice of the refractive index $n_{arc}$ and the thickness of the thin layer can lead to the limiting case of destructive or constructive interference of reflected waves [3].

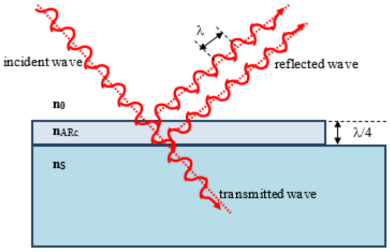


Fig.1. Stacking of anti-reflection layers.

## Choice of refractive index

In order to choose the material of the ARC, the relationship between the refractive indices $n_1$, and $n_3$ of air, antireflective layer and silicon respectively should be searched. As an example, titanium dioxide ($TiO_2$) has suitable characteristics for making an anti-reflective layer and has therefore been widely used in the photovoltaic industry.

**Table 1. Variation of the refractive indices of the antireflection layers**[3].

| anti-reflective materials | Wavelengths (nm) | Refractive indexes |
|---|---|---|
| $MgF_2$ | 400 – 800 | 1,3839 – 1,3751 |
| $SiO_2$ | 400 – 800 | 1,4701 – 1,4553 |
| ZnO | 450 – 800 | 2,1054 – 1,9591 |

| | | |
|---|---|---|
| $TiO_2$ | 430 – 800 | 2,8717 – 2,5197 |
| ZnS | 405 – 800 | 2,5434 – 2,3132 |
| $Si_3N_4$ | 400 – 800 | 2,1004 – 2,0242 |
| $ZrO_2$ | 400 – 800 | 2, 0825 - 2,1494 |
| Si | 400 – 800 | 5,5674 - 3,6941 |

Table 1. represents the variation of refractive indices of a number of antireflective materials ($Si_3N_4$, $TiO_2$, $SiO_2$, $ZrO_2$, ZnS, Si), in the wavelength range from 400 nm to 1100 nm. Silicon has higher index values than materials like titanium oxide ($TiO_2$), and zinc sulfide (ZnS). These materials can be used as an anti-reflective coating.

## Representation of the refractive indices on the materials used as antireflection layers.

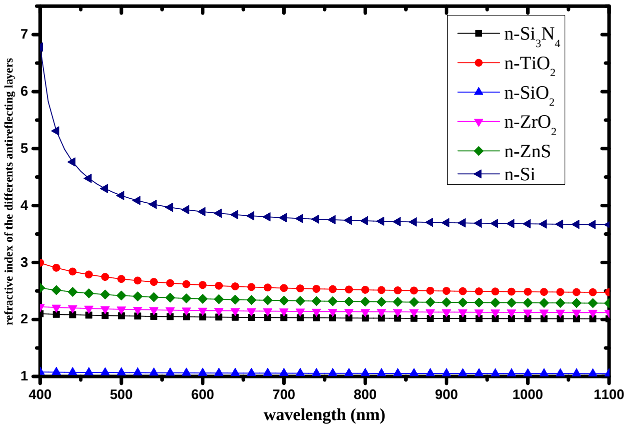


Fig.2. Refractive index of the different antireflective materials used as a function of wavelength.

We note a large difference between the variation of the refractive index of silicon and that of anti-reflective layers as a function of the wavelength with a slight decrease.

## Theoretical study on antireflective multilayers

### Reminder on the interferential Stacks

The characteristic approach used, relates the total tangential components of the electric and magnetic fields to the boundaries between two layers. The structure of a multilayer completely determines the characteristic matrix. This approach is more general and can handle a large number of interfaces.

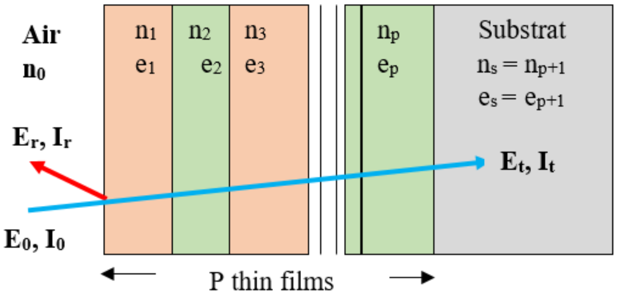


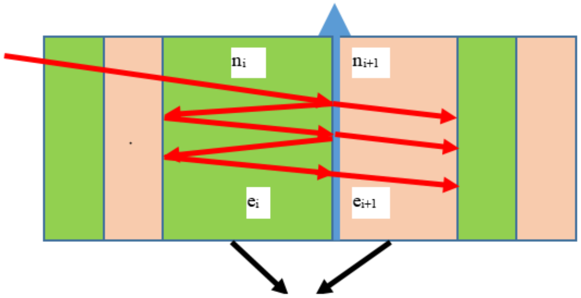
Fig.3. Stacking of anti-reflection layers[10].

Fig. 3 shows a stack of p layers deposited on a substrate of index ns, each layer is characterized by a refractive index np and a thickness ep, the incident ray angle being between 0 and 65°. Subsequently, the study of the behavior of reflected and refracted rays in parallel polarization is the same as those in transverse polarization.

## The diopter between two layers

### Phase shift of the waves

The diopters separating the layers make it possible to divide the incident wave, and then recombine the reflected or transmitted beams with a phase shift which is at the origin of the interferences between these various beams.



The thicknesses allow the different beams to be dephased

Fig.4. The waves reflected and transmitted by a diopter

If we consider two successive layers i and i +1, of respective indices $n_i$ and $n_{i+1}$.

### Amplitude of the beams at the crossing of a diopter

The diopter separating two layers of materials of indices ni and ni+1 is schematized in Fig.5.

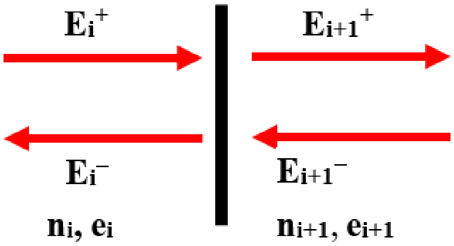


Fig.5. Amplitudes of the beams at the crossing of a diopter

The amplitudes of the incident and reflected waves in layer i are respectively E+i and Ei and those transmitted and incident in layer i + 1, are E+i+1 and Ei+1. The relations of the passage of electromagnetism give:

$$\left| E^{+;i+1} = t_{i\rightarrow i+1} . E^{+;i+1} + r_{i+1\rightarrow i} . E^{-;i+1} ; E^{-;i} = r_{i\rightarrow i+1} E^{+;i} + t_{i+1\rightarrow i} E^{-;i+1} \right. \quad (1)$$

We derive the following relationships for the amplitudes of the incident, reflected and transmitted fields

**Error!** (2)

Equation 2 can be rewritten in the following matrix form:

**Error!**(3)

With **Error!**

the matrix associated with the diopter between the layers i et i+1.

### Study of the amplitudes of radiation at the crossing of a layer

The amplitude of a wave passing through a layer of material of thickness $e_i$ between the diopters $x_i$ and $x_{i+1}$ is given by the following relation:

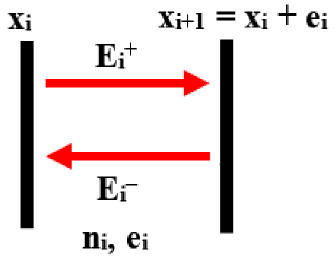


Fig.5. The waves reflected and transmitted by a diopter

**Error!** (4)

$$E^{+;i}(x_{i+1}) = E^{+;i}(x_i)\exp(-jj_i) \quad (5)$$

$$E^{-;i}(x_{i+1}) = E^{-;i}(x_i)\exp(j\varphi_i)) \quad (6)$$

With **Error!**, the phase shift between the beams at xi and xi+1 and introduced by the layer.
In matrix form, we write:

$$\left(E^{-;i};E^{+;i}\right) = \left(e^{-j\varphi}{}_{i};0;0_{;}\ e^{-j\varphi}{}_{i}\right)\left(E^{-;i+1};E^{+;i+1}\right) = C_i\left(E^{-;i+1};E^{+;i+1}\right) \quad (7)$$

$$x_i \qquad\qquad x_{i+1} \qquad\qquad x_{i+1}$$

$C_i$ is the matrix associated with the layer i.

### Progression of the field amplitudes in the stack

Fig.6 details the progression of the beam amplitudes in the different layers of the stack.

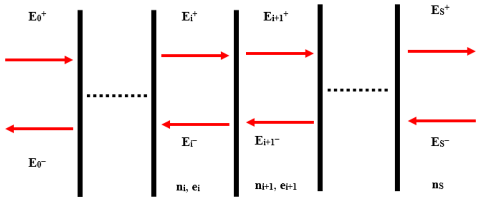


Fig. 6: Progression of the amplitudes Ei of the waves in the stack with the hypothesis $E_S- = 0$

The total amplitude of the reflected and refracted radiation in a stack of several layers is the product of all the amplitudes at the crossing of the diopters and layers [4,5,6,7,8]. This results in a matrix relation linking the amplitudes E+0 and E0 of the incident and reflected beams on the input face and the amplitude E+s of the transmitted beam in the substrate, under the assumption that there is no reflected wave in the substrate (Es = 0) (Fig. 7).

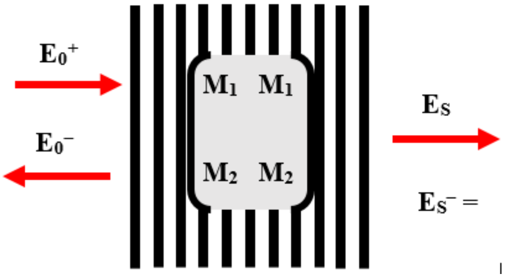


Fig.7: Schematic representation of the general configuration
of the multilayers with the associated matrix

The matrix is then written: $M = D_0.C_1.D_1.C_2.\dots.C_p.D_p$

$$(E^{-;0};E^{+;0}) = (M_{11};\ M_{12};M_{21;}M_{22}\qquad)\ (0;E^{+;t}) = M\ (0;E^{+;t})\ (8)$$

The reflection coefficient in amplitude of the stack is obtained from the elements $M_{12}$ and $M_{22}$ of the matrix, that is $r = M_{12}/M_{22}$, while the transmission coefficient is given by $t = 1/M_{22}$.
The reflection and transmission coefficients in intensity are $R = r.r^*$ and $T = t.t^*$.

In the continuation, the matrix relation (8) will be used to carry out a program on Mathcad in order to study the reflectivity and the transmission of the antireflection layers. Their influence on the quantum efficiency of solar cells will be examined. The calculations will be carried out by considering two possibilities of applications: the case of a cell with an anti-reflection monolayer, i.e. a cell encapsulated or not, and then the case of a cell with a non-encapsulated anti-reflection multilayer[9, 10,11,12,13].

## Conclusion

In this paper, we succeeded in building a program that allowed us to see the influence of the reflectivity, transmission and absorption of RACs and MCARs on the efficiency of solar cells. The calculations were carried out considering the two possible applications for a cell with an anti-reflective monolayer, i.e. for an encapsulated or non-encapsulated cell (n0 = 1). Thus, for a cell with a non-encapsulated anti-reflective multilayer. As a first step, we made a program where we neglected the influence of the absorption of the layers. But the high refractive indices necessary for the realization of these multilayers will inevitably induce a strong absorption of high-energy photons. This is why we introduced the absorption equations into the program.

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