Assessment of the radiative properties of some semi-conductors for applications in thermophotovoltaic and thermophotonic conversion systems

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Abstract

Today, major energy challenge is to find alternatives to exhaustible and polluting fossil fuels. Photovoltaic (PV), thermophotovoltaic (TPV) and thermophotonic (TPX) systems offer interesting prospects for the purpose. However, these technologies require a judicious choice of the emitting materials. This paper presents an assessment of the radiative properties of some semi-conductors that can be used for these systems. The method is based on the principles of thermal radiation, Fresnel's theories of radiation, and Maxwell's equations describing the classical theory of the propagation of electromagnetic waves in a homogeneous and isotropic medium. The influence of the extinction index on the optical characteristics of some materials (SiC, Si, Ge, and ZnO) is evaluated. The transfer matrix method was used to evaluate and assess the behaviour of the radiative properties of strongly and weakly absorbing multilayered structures. It was found that the use of a non-reflecting treatment (glass or ZnO) on the material, enables to reduce multiple reflections and therefore to improve the efficiency of the system.

Keywords: *Semi-Conductors; Thermal Radiation; Energy Conversion Systems; Photovoltaic; Thermophotovoltaics; Thermophotonics.*

1. Introduction

The ever-increasing demand for conventional energy sources like coal, natural gas and crude oil is driving society towards the research and development of alternate energy sources. TPV and TPX systems offer interesting prospects for the purpose. However, these technologies require a judicious choice of the emitting material. Thermophotovoltaics involves the photovoltaic conversion of radiation from an emitter heated by various sources including sunlight. The main difference from the normal solar photovoltaics is that, the emitted energy unable to be used by the receiver can be recycled allowing high conversion efficiency. Thermophotonics is a recent development of this concept. Here, the emitter (heated diode) is "active", increasing therefore the rate of energy transfer for a given emitter temperature and concentrating the emission in an energy range more suited for conversion by the cell [1], [2].

Few works related to TPV and TPX systems are found in the literature. These essential engineering disciplines include areas such as heat and mass transfer, optics with infrared filters, high temperature materials with ceramics, incandescent lamp with vacuum designs and radiant burners [2]. Green [5] was the first to propose publicly in a forum, works on TPX in 2000. Nowadays, no TPX device is known to have been designed because of the difficulty of operation at very high temperature with sufficient efficiency [3], [5]. Most research groups focus on cells from Gallium Antimonide (GaSb), Silicon (Si), and Gallium Arsenide Indium (InGa-As). The germanium (Ge) is also cost effective [6].

The main element in the TPV and TPX conversion system is the selective emitter i.e. a heat source which emit very intensely in a given spectral band closed to the gap of the photosensitive material, and not elsewhere [8]. Most of the

research and development in TPV and TPX systems are related to methods of controlling the properties of the emitter which is very important to the overall efficiency of the system. Drevillon et al [7] used genetic algorithms to propose some solutions, but the resulting structures are too complex since they consist of many layers. Indeed, it was recently shown that one can have very different thermal radiation from that of a black element by controlling it spectrally and directionally [9]. Thus the importance of the theory of electromagnetic waves is incontestable in order to obtain the specific optical properties of the material at the interface (transmitter). The energy transfer between the components of TPV or TPX system is mainly made up of thermal radiation which propagates in the form of electromagnetic waves to a PV cell [10]. For an ideal case of TPV and TPX systems, it is necessary to work on the properties of emission sources and suitable materials for these systems.

In this paper, we are investigating into the radiative properties of some semi-conductors for TPV and TPX applications. The method is based on the principles of thermal radiation, Fresnel's theories of radiation, and Maxwell equations describing the classical theory of the propagation of electromagnetic waves in homogeneous and isotropic media.

2. Modeling of thermal radiation in a multilayered material

2.1. Optical properties of thermal radiation

The optical properties of materials are governed by three main phenomena: transmission, reflection and absorption (figure 1). These phenomena are respectively characterized by a transmittance or transmission factor (T), a reflectance or reflection factor (R), an absorbance or absorption factors (A) [11]. These parameters are important for TPV and TPX systems. They help to evaluate and control the electromagnetic waves or the incident light, so that to get a maximum emissivity, which will be emitted toward the TPV or TPX cell.
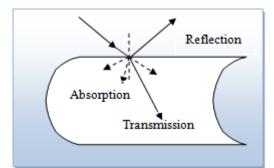

Fig. 1: Reflection, Transmission and Absorption of Radiation [12].

A thermal radiation is defined by some fundamental laws. The spectral radiance $L_\lambda^0(\lambda,T)$ of the black element radiation is isotropic and given by Planck's law as follows [13]:

$$M_\lambda^0(\lambda,T) = \pi L_\lambda^0(\lambda,T) = \frac{2\pi h_p \lambda^{-5}}{\exp\left(h_p c / k_B \lambda T\right) - 1} \tag{1}$$

The total luminance is obtained by integrating through the entire wavelengths of the monochromatic luminance; and the Stephan-Boltzmann's law is obtained [13]:

$$L^0 = \int_0^\infty \frac{2.\pi.h c^2.\lambda^{-5}}{\exp\left(h c / k_B \lambda T\right) - 1} d\lambda = \sigma T^4 \tag{2}$$

Taking into account Wien's theory related to the monochromatic luminance of a black body, Planck's formula can be approximated by [14]:

$$M_\lambda^0 = 2.\pi c^2.\lambda^{-5}.\exp\left(-h c / k_B \lambda T\right) \tag{3}$$

The first law of Wien related to thermal radiation is given by [14]:

$$\lambda_{\max} T = 2898 \; \mu m.K = cst \tag{4}$$

While the second law of Wien is [14]:

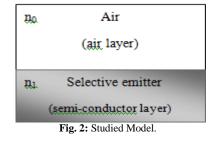$$M_{\lambda_m}^0 = 1.287.10^{-5} T^5 \; W.m^{-3} \tag{5}$$

Kirchhoff's law describing the relationship between the emission and absorption is given by [15]:

$$\varepsilon(\lambda,\theta,\varphi) = \alpha(\lambda,\theta,\varphi)$$

Where $\varepsilon(\lambda,\theta,\varphi)$ are the monochromatic directional emissivity and $\alpha(\lambda,\theta,\varphi)$ the monochromatic directional absorptivity? This law is valid only if one assumes local thermodynamic equilibrium. If the surface is in thermodynamic equilibrium, the Kirchhoff's law can be used and we have [15]:

$$1 = r(\lambda,\theta,\varphi) + \tau(\lambda,\theta,\varphi) + \varepsilon(\lambda,\theta,\varphi) \tag{6}$$

For opaque surfaces, $\tau = 0$ thus:

$$\varepsilon(\lambda,\theta,\varphi) = 1 - r(\lambda,\theta,\varphi) \tag{7}$$

2.2. Studied model

Figure 2 shows the model used to study the radiative properties (reflection, transmission, absorption) of the semiconductors in the case of high and low absorption.

Fig. 2: Studied Model.

The radiative properties of the structure are evaluated by the transfer matrix method. This method is based on the propagation of the electromagnetic field in an optically isotropic homogeneous structure and modelled by Maxwell's relations. It helps to understand the usefulness of the antireflection layer that allows the reduction of losses due to reflection.

3. Transfer matrix method

The propagation of the electromagnetic field within a homogeneous optically and isotropic structure is described by the Maxwell's relations. The following equation called D'Alembert is used [16]:

$$\Delta \vec{E} - \mu_0.\mu_r.\sigma \frac{\partial \vec{E}}{\partial t} - \mu_0.\mu_r.\varepsilon_0.\varepsilon_r \frac{\partial^2 \vec{E}}{\partial^2 t^2} = \vec{0} \tag{8}$$

The wavelength in the vacuum $\lambda = 2.\pi c / \omega$ of frequency $v = \omega / 2.\pi$ and with a wave vector $\vec{k}$ directed along the direction of propagation is defined such that ($\vec{E}$, $\vec{H}$ $\vec{k}$) is a direct trihedral. K is linked to the pulsation by the relation:

$$k = n\omega / c \tag{9}$$

The multilayered system shown in figure 3 is annotated by the components of the electric field at each interface. For the sake of convenience, this figure is oriented such that the incident waves propagate from the left to the right. The '+' and '-' are used to distinguish the incident waves to reflected one. Signs (') are used to distinguish the waves that are at the right side of an interface from those of the left side.

Fig. 3: A Multi-layered Structure Used to Illustrate the Principle of the Matrix Transfer Method.

The multi-layered structure is made of N + 1 interfaces and N layers. The layer of the extreme left side is assumed to be air (n0 = 1) and the far right the substrate. The boundary conditions for the vectors of the electric field E at each side of any interface allows a simple description by a 2x2 matrix. Thus, for the kth interface, the relationship between the components of the field is given by:

$$\begin{pmatrix} E_{k-1}^+ \\ E_{k-1}^- \end{pmatrix} = D_{k-1,k} \begin{pmatrix} E_k'^+ \\ E_k'^- \end{pmatrix} \tag{10}$$

Where $D_{k-1,k} = \dfrac{1}{t_{k-1,k}} \begin{pmatrix} 1 & r_{k-1,k} \\ r_{k-1,k} & 1 \end{pmatrix}$

The field components at the left and right sides of the k-th layer are defined by the propagation matrix Pk:

$$\begin{pmatrix} E'^{+}_{k} \\ E'^{-}_{k} \end{pmatrix} = p_k \begin{pmatrix} E^{+}_{k} \\ E^{-}_{k} \end{pmatrix}$$

(11)

With $P_k = \begin{pmatrix} \exp(i\,.\varphi_k) & 0 \\ 0 & \exp(-i\,.\varphi_k) \end{pmatrix}$

$\varphi_k = \dfrac{2.\pi.n_k \cos(\theta_k)}{\lambda} d_k$ Represents the dephasing for $\theta \neq 0$

λ is the wavelength in the medium.

For k layers, the Fresnel coefficients are written:

For a parallel polarization:

$$r^{s}_{k} = \frac{E^{s}_{k-1,r}}{E^{s}_{k-1,i}} \text{ And } t^{s}_{k} = \frac{E^{s}_{k,i}}{E^{s}_{k-1,i}}$$

(12)

For a perpendicular polarisation:

$$r^{p}_{k} = \frac{E^{p}_{k-1,r}}{E^{p}_{k-1,i}} \text{ And } t^{p}_{k} = \frac{E^{p}_{k,i}}{E^{p}_{k-1,i}}$$

(13)

These coefficients are expressed as functions of the refractive indexes nk-1 and nk of the layers using Fresnel laws as follows:

$$r^{s}_{k} = \frac{n_{k-1}\cos(\theta_k) - n_k \cos(\theta_{k-1})}{n_{k-1}\cos(\theta_k) + n_k \cos(\theta_{k-1})} \qquad t^{s}_{k} = \frac{2n_{k-1}\cos(\theta_{k-1})}{n_{k-1}\cos(\theta_k) + n_k \cos(\theta_{k-1})}$$

(14)

$$r^{p}_{k} = \frac{n_{k-1}\cos(\theta_{k-1}) - n_k \cos(\theta_k)}{n_{k-1}\cos(\theta_{k-1}) + n_k \cos(\theta_k)} \qquad t^{p}_{k} = \frac{2n_{k-1}\cos(\theta_{k-1})}{n_{k-1}\cos(\theta_{k-1}) + n_k \cos(\theta_k)}$$

(15)

In the case of normal incidence $\theta_k = 0$, the values of the Fresnel coefficients are independent to the polarization condition [16]:

$$r^{s}_{k} = r^{p}_{k} = \frac{n_{k-1} - n_k}{n_{k-1} - n_k} \qquad t^{s}_{k} = t^{p}_{k} = \frac{2}{n_{k-1} - n_k}$$

(16)

For $\theta = 0$, the dephasing is of the form:

$$\varphi_k = \frac{2.\pi.n_k}{\lambda} d_k$$

(17)

However, these quantities are generally complex. The coefficients of reflection and transmission are determined assuming that:

$$E^{-}_{0} = E'^{-}_{N+1} = 0$$

The energy conservation equation gives:

$$|r|^2 + |t|^2 = 1$$

Consequently,

$$R = |r|^2 \text{ And } T = |t|^2$$

4. Reflection and transmission at the interface between two homogeneous media

Let's consider an interface between two semi-infinite media (an environment of index ñ1 and an isotropic material with complex index ñ2 as shown in Figure 2. The refractive index is defined by its real part n2 and its imaginary part K2, respectively called the refractive index and extinction coefficient.

ñ2 = n2− i k2   (18)

For a normal incident angle:

$$R = R_{TE} = R_{TM} = \left[\frac{\tilde{n}_1 - \tilde{n}_2}{\tilde{n}_1 + \tilde{n}_2}\right]^2 \qquad T = T_{TE} = T_{TM} = \left(\frac{2\tilde{n}_1}{\tilde{n}_1 + \tilde{n}_2}\right)^2 \frac{\tilde{n}_2}{\tilde{n}_1} \qquad (19)$$

For example, in the case of Silicon (Si), the dioptre air-silicon gives:

ñ1 = 1 and ñ2 = n_{Si} – i k_{Si}

The reflection coefficient becomes:

$$R = \frac{(1 - n_{si})^2 + k_{si}^2}{(1 + n_{si})^2 + k_{si}^2} \qquad (20)$$

5. Modeling of the anti-reflection layer

To reduce or cancel the reflections, the condition of destructive interference (r12=-r21) is required. This relation is called the principle of layers' antireflection [13]. When the dephasing is φ = ± π, the expression of the thickness of the layer is obtained through:

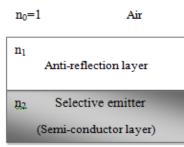$$\widetilde{n_1} = 1 \qquad d = \lambda/4n_2 \qquad (21)$$

Fig. 4: A Multilayered Structure Consisting of an Antireflection Layer (Glass, Zno) and a Selective Emitter (Si).

6. Results and discussion

A SCILAB program was developed to assess the various radiative parameters. The results are presented in this section.

6.1. Influence of the extinction index for normal incidence

In practice, to measure the reflection coefficient in the case of low absorption, one side of a prism material is used. Indeed, the use of a parallel plate leads to multiple reflections with interferences. In the case of high absorption, one can just use a blade of sufficient thickness to completely absorb the transmitted wave.

Fig. 5 presents the variation of the reflection coefficient with the extinction index for air and various semiconductors (ZnO, SiC, Si, Ge).
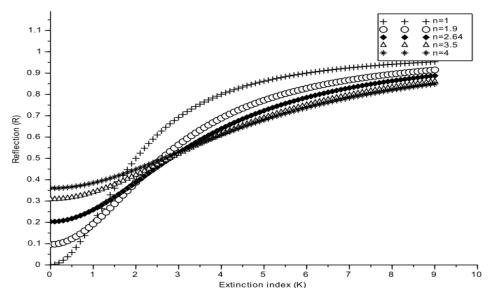

Fig. 5: Variation of the Reflection Coefficient with the Extinction Index for Air and Some Semi-Conductors (Zno, Sic, Si, Ge).

As shown in fig. 5 and table 1, it could be seen that the reflection coefficient is highly influenced by the extinction index (K). According to the type of the material, the reflection coefficient range from 0.1 to 0.9. For an extinction index of 2.6, the materials (ZnO, SiC, Si, Ge) have practically the same reflection coefficient (R=0.5). In practice the best suited material should have little reflection coefficient, so SiC, Si, and Ge may be used in the TPV and TPX systems. In addition, the Germanium could support very high temperature compared to the two other.

Table 1: Influence of the Extinction Index (K) Corresponding to Each Material.

Material	Air	ZnO	SiC	Si	Ge
Normal index of refraction (n)	1	1.9	2.64	3.5	4
Range of the reflection coefficient	0 - 0.95	0.1 -0.9	0.2 - 0.78	0.3 - 0.76	0.35 -0.75

6.2. Influence of the ratio (e/λ) on the reflection, transmission and absorption coefficients

6.2.1. Case of low absorption (K<1)

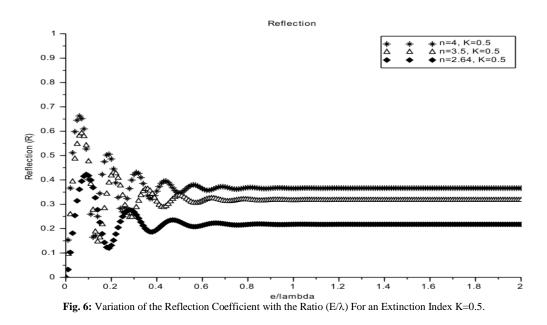In this case, the optical properties are mainly influenced by the index n, which is different to 1.

Fig. 6: Variation of the Reflection Coefficient with the Ratio (E/λ) For an Extinction Index K=0.5.

Figure 6 presents the variation of reflection coefficient with the ratio (e/λ) for an extinction index K = 0.5 in the case of low absorption for the germanium (Ge), the Silicon (Si) and the Silicon carbide (SiC). It could be seen from fig. 6 and table 2 that in the case of low absorption, the reflection coefficient fluctuates for $0 \leq e/\lambda \leq 0.6$ and more constant for e/λ> 0.6. In addition, the SiC has interesting reflection coefficient compared to the two others.

Table 2: Range of the Reflection Coefficient in the Case of Low Absorption for Some Materials (Ge, Si, Sic).

Material	Ge	Si	SiC
Reflection coefficient (R)	0-0.38	0-0.35	0-0.2
Ratio (e/λ)	0 -0.78	0-0.75	0-0.7

Figure 7 presents the variation of the transmission coefficient of some semi-conductors (Ge, Si, SiC) with the ratio (e/λ) in the case of low absorption for an extinction coefficient K=0.5.

Fig. 7: Variation of the Transmission Coefficient of Some Semi-Conductors (Ge, Si, Sic) with the Ratio (E/λ) in the Case of Low Absorption for an Extinction Coefficient K=0.5.
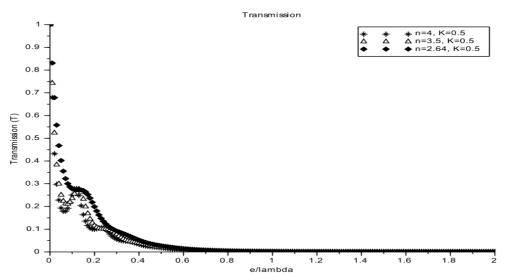
It could be seen from fig. 7 and table 3 that in the case of low absorption, the transmission coefficient fluctuates for $0 \leq e/\lambda \leq 0.6$ and more constant for $e/\lambda > 0.6$. From the same table, it is seen that the ranges of the transmission coefficient and thicknesses are practically the same.

In general, for TPV and TPX systems, layers with large thickness make that the transmitted wave is not completely absorbed by the material. So there will not be a good heat exchange between the emitter and the TPV or TPX cell.

Table 3: Range of the Transmission Coefficient in the Case of Low Absorption for Some Semi-Conductors (Ge, Si, Sic).

Material	Ge	Si	SiC
Transmission coefficient (T)	0-0.9	0-0.9	0-0.9
Ratio (e/(λ)	0-0.8	0-0.8	0-0.8

Figure 8 shows the variation of the absorption coefficient of some semi-conductors (Ge, Si, SiC) with the ratio (e/λ) in the case of low absorption for an extinction coefficient K=0.5.

Fig. 8: Variation of the Absorption Coefficient of Some Semi-Conductors (Ge, Si, Sic) with the Ratio (E/λ) in the Case of Low Absorption for an Extinction Coefficient K=0.5.
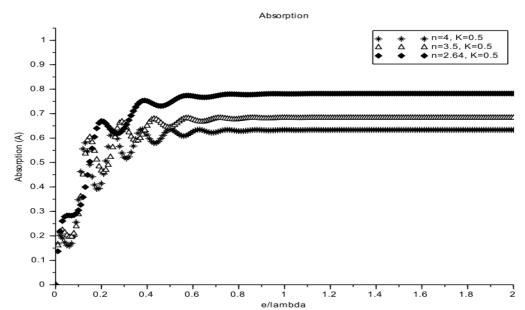
It could be seen from fig. 8 and table 4 that in the case of low absorption, the absorption coefficient fluctuates for $0 \leq e/\lambda \leq 0.6$ and more constant for $e/\lambda > 0.6$. It is seen from table 4 that SiC and Si present interesting characteristics. In fact, low absorptivity yields to poor performance of the TPV and TPX systems. The problem is most of the time solved by a specific antireflection treatment as presented in section 6.3.

Material	Ge	Si	SiC
Range of absorption coefficient (A)	0.05-0.63	0.05-0.65	0.05-0.75
Ratio (e/λ)	0-0.85	0-0.85	0-0.75

6.2.2. Case of high absorption (K>1)

Unlike the case of low absorption which causes multiple oscillations, high absorption generates fewer oscillations. In this case, the extinction index is greater than one.

Figure 9 shows the variation of the reflection coefficient of some semi-conductors (Ge, Si, SiC) with the ratio (e/λ) in the case of high absorption for an extinction coefficient K=5.

Fig. 9: Variation of the Reflection Coefficient of Some Semi-Conductors (Ge, Si, Sic) with the Ratio (E/λ) in the Case of High Absorption for an Extinction Coefficient K=0.5.
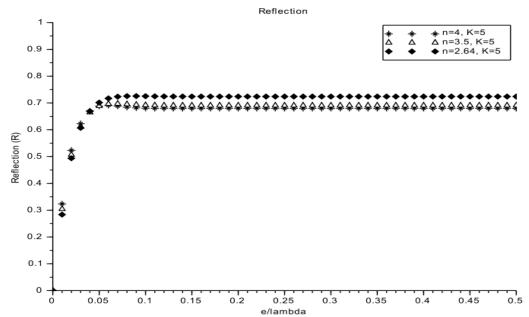
It could be seen from fig. 9 and table 5 that in the case of high absorption, the reflection coefficient fluctuates for $0 \leq e/\lambda \leq 0.06$ and more constant for $e/\lambda > 0.06$. In this case, reflection does not present a minimum. So, TPV and TPX systems with this kind of reflection will have a low absorption, consequently a low efficiency.

Table 1: Range of Reflection Coefficient of Some Semi-Conductors (Ge, Si, Sic) in the Case of High Absorption.

Material	Ge	Si	SiC
Range of reflection coefficient (R)	0-0.68	0-0.7	0-0.73
Ratio (e/λ)	0-0.08	0-0.07	0-0.05

Figure 10 shows the variation of the transmission coefficient of some semi-conductors (Ge, Si, SiC) with the ratio (e/λ) in the case of high absorption for an extinction coefficient K=5.

Fig. 10: Variation of the Transmission Coefficient of Some Semi-Conductors (Ge, Si, Sic) with the Ratio (E/λ) in the Case of High Absorption for an Extinction Coefficient K=5.
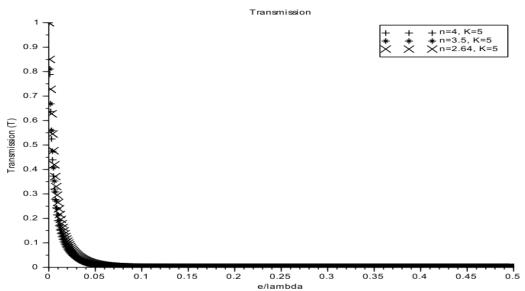
It could be seen from fig. 10 and table 6 that in the case of high absorption, the transmission coefficient fluctuates for $0 \leq e/\lambda \leq 0.06$ and more constant for $e/\lambda > 0.06$. The same remarks as in the case of low absorption are made.

Table 6: Range of Transmission Coefficient of Some Semi-Conductors (Ge, Si, Sic) in the Case of High Absorption

Material	Ge	Si	SiC
Range of transmission coefficient (T)	0-0.8	0-0.8	0-0.8
Ratio (e/λ)	0-0.09	0-0.09	0-0.09

Figure 11 shows the variation of the absorption coefficient of some semi-conductors (Ge, Si, SiC) with the ratio (e/λ) in the case of high absorption for an extinction coefficient K=5.

Fig. 11: Variation of the Absorption Coefficient of Some Semi-Conductors (Ge, Si, Sic) with the Ratio (E/λ) in the Case of High Absorption for n Extinction Coefficient K=5.

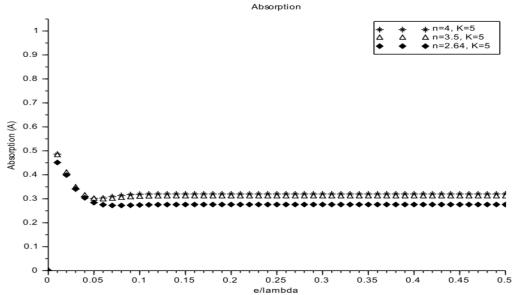It could be seen from fig. 11 and table 7 that in the case of high absorption, the absorption coefficient fluctuates for $0 \leq e/\lambda \leq 0.06$ and more constant for $e/\lambda > 0.06$. The results are in conformity with the law of Kirchhoff which says that a good absorber is also a good emitter. Systems operating in this condition present a good efficiency.

Table 7: Range of Absorption Coefficient of Some Semi-Conductors (Ge, Si, Sic) in the Case of High Absorption.

Material	Ge	Si	SiC
Range of absorption coefficient (A)	0.11-0.32	0.11-0.31	0.11-0.30
Ratio (e/λ)	0-0.07	0-0.06	0-0.05

6.3. Antireflection treatment at the interface

To minimize multiple reflections, an antireflective treatment is sometimes needed. In this study we will consider the case of a glass and the ZnO.
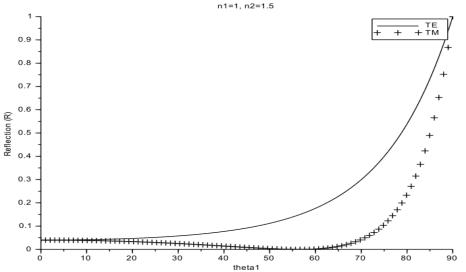
6.3.1. Case of a glass layer

Fig. 12: Fresnel Factors of Reflection for a Radiative Energy Reflected on the Surface of Silicon in the Visible Range Using a Glass Layer as Antireflection Treatment.

In Figure 12, the plain curve represents the TE polarization, and the dot curve the TM polarization. In TM polarization, there is practically a cancellation of reflection at the brewsterian angle 56.3°; the reflection coefficient here has a value R = 0.04. When θi tends to 90°, the two coefficients tend to 1.

Fig. 13 presents the case of a treatment using a glass antireflective layer with a thickness equals to the quarter of wavelength value. It could be seen that in this case, the reflectance is zero for the two polarizations (TM and TE) at a Brewster angle of 56° in contrast to the case presented in figure 12 where there a cancellation reflectance only in TM polarization. Reflection in this case is reduced to R=0.01.
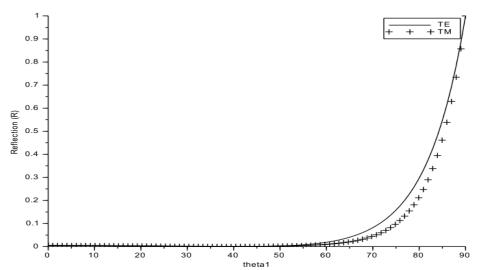

Fig. 13: Representation of the Antireflection Curve for a Thickness Equals to the Quarter of the Wavelength Value in the Case of an Antireflective Treatment with Glass.
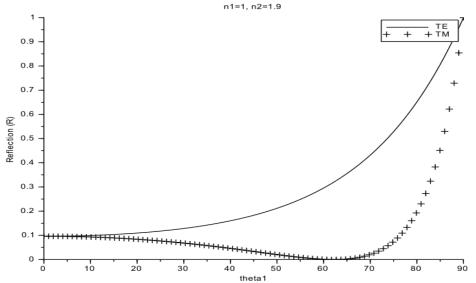
6.3.2. Case of zinc oxide (ZnO)

Fig. 14: Fresnel Factors of Reflection for a Radiative Energy Reflected on the Surface of Silicon in the Visible Range Using a Zinc Oxide as Antireflection Treatment.

In Figure 14, the plain curve represents the TE polarization, and the dot curve the TM polarization. In TM polarization, it could be observed a cancellation of reflection at a brewsterian angle $\theta_B = 62.24^0$ where the reflection coefficient's value is R = 0.1

Fig. 15 presents the case of a treatment using a ZnO antireflective layer with a thickness equals to the quarter of wavelength value. Here, there is no cancellation of the reflectance at the two polarizations (TM and TE) at the Brewster angle. The reflectance value is R = 0.03
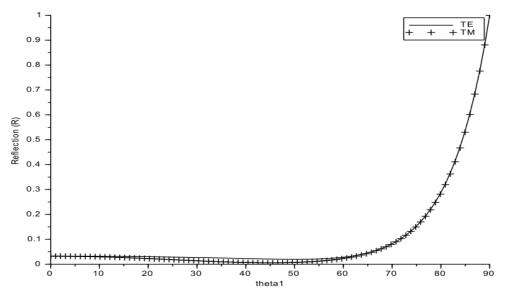

Fig. 15: Representation of the Antireflection Curve in for A Thickness Equals to the Quarter of the Wavelength Value in the Case of an Antireflective Treatment with ZnO.

Table 8 present a brief summary of the anti-reflective treatment. It could be seen that using glass for an antireflective treatment is better than ZnO.

Table 8: Summary of the Parameters of the Antireflection Treatment.

Material	ZnO	Glass
Index of the material (n_s)	1.9	1.5
Ideal Index of the material (n_1)	1.37	1.22
Untreated Reflectance (R)	0.1	0.04
Treated Reflectance (R)	0.03	0.013

7.   Conclusion

In this paper we presented an assessment of the radiative properties of some semi-conductors that can be used in TPV and TPX systems. The method was based on the principles of thermal radiation, Fresnel's theories of radiation, and Maxwell's equations describing the classical theory of the propagation of electromagnetic waves in a homogeneous and isotropic medium. The influence of the extinction index on the optical characteristics of some materials (SiC, Si, Ge, and ZnO) was evaluated. The transfer matrix method implemented in under a scilab platform was used to evaluate and assess the behaviour of the radiative properties of strongly and weakly absorbing multilayered structures. It was found that the use of a non-reflecting treatment (glass or ZnO) on the material, enables to reduce multiple reflections and therefore to improve the efficiency of the system.

Nomenclature

D_k : Stamp passage of the kth layer

d_k : Thickness of the kth layer (μm)

$\vec{E}$: Electric field

E_k : Electric field of the kth layer

E_k^s : Electric field in parallel polarization of the kth layer

E_k^p : Electric field in perpendicular polarization of the kth layer

e : Thickness

K : Index of extinction

k : Amplitude of the vector of wave

L^0 : Total Brightness

L_λ^0 : Spectral brightness

$L_\lambda^{'0}$: Spectral brightness in the vacuum

$M_{\lambda m}^0$: Monochromatic flux density total

M_λ^0 : Monochromatic flux density

n : Index of refraction

n_k : Index of refraction of the kth layer

p_k : Stamp propagation of the kth layer

R: Factor of reflection (%)

$r(\lambda,\theta,\phi)$: Coefficient of directional reflectivity

r_k^s : Reflection in parallel polarization of the kth layer

r_k^p : Reflection in perpendicular polarization of the kth layer

$_r$: Coefficient of reflection of Fresnel (%)

T: Factor of transmission (%)

T: Temperature (K)

t_k^s : Transmission in parallel polarization of the kth layer

t_k^p : Transmission in perpendicular polarization of the kth layer

Greek symbols

θ_l : Limit angle (^{o})

θ_B : Brewster's angle (^{o})

θ : Angle of incidence

θ_k : Angle of incidence of the kth layer

λ : Wavelength (μm)

τ : Coefficient of transmission of Fresnel (%)

σ : Conductivity of the medium

$\varepsilon(\lambda,\theta,\phi)$: Directional and monochromatic emissivity

$\tau(\lambda,\theta,\phi)$: Coefficient of directional transmissivity

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