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Study the Effect of a Single Layer of Anti-reflective Coating (Ge) on the Quantitative Efficiency of a Silicon Solar Cell

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Abstract
The objective of this research is to study the possibility of reducing the reflectivity of the front surface of a silicon cell (Si / Si) by using a theoretical design for a single-layer Antireflection Coatings with a thickness of one quarter of the design wavelength. Then, Mathematical programs in MATLAB (10) were designed to study the quantitative efficiency of the cell as a function of the change in the particle size of the coating within the range (400 - 700 nm) wavelength of the visible state of the vertical and oblique state at the (45°) angle. (Ge) was used as an anti-reflective material. It was found that the highest quantitative efficiency was (96.9004%) at design wavelength (λ_0= 550 nm) in the case of vertical fall. Whereas, in the case of a sloping fall at an angle of (45^o), a quantitative efficiency of (94.0545%) at vertical polarization (S). In the case of horizontal polarization (P), the quantitative efficiency value is (96.3131%) when the particle size of the coating is (Ps = 4.4nm).

Keywords: Quantum efficiency, solar cell, anti-reflective coating, Germanium

دراسة تأثير طبقة مفردة لطلاء مضاد للانعكاس من مادة (Ge)على الكفاءة الكمية لخلية شمسية من السليكون

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الخلاصـــة
الهدف من البحث هو دراسة امكانية تقليل انعكاسية السطح الأمامي لخلية شمسية من السيلكون (Si/Si) عن طريق استخدام تصميم نظري لطلاء مضاد للانعكاس (Antireflection Coatings) ذات طبقة مفردة بسمك ربع طول موجة التصميم. تم تصميم برامج رياضية بلغة (MATLAB) النسخة (10) لدراسة الكفاءة الكمية (Quantitative Efficiency) لتلك الخلية كدالة للتغير في الحجم الحبيبي لمادة الطلاء ضمن المدى (400 – 700 nm) من الطول الموجي للأشعة المرئية لحالة السقوط العامودي والمائل عند زاوية 45^o.استخدم الجرمانيوم(Ge) كمادة مضادة للانعكاس, وجد أن اعلى كفاءة كمية بمقدار (96.9004%) عند طول موجة التصميم (λ_o = 550 nm)في حالة السقوط العمودي، وفي حالة السقوط المائل وبزاوية (45^o)، فقد تم الحصول على كفاءة كمية بمقدار(94.0545%) عند الاستقطاب العمودي (S) وفي حالة الاستقطاب الافقي (P) اصحبت قيمة الكفاءة الكمية تساوي(96.3131%) عندما يكون الحجم الحبيبي لمادة الطلاء (Ps=4.4nm).

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Introduction

By using nanotechnologies we can acquire materials that possess new visual properties that cannot be combined in traditional materials. This technology is concerned with materials, structures and systems whose components exhibit new and changing physical and chemical properties at nanomaterial sizes. These properties can be invested in the design and improvement of optical coatings and their use in scientific applications [1].

Solar cells are one of the most famous applications of solar energy, and the work of the solar cell depends on the photovoltaic effect [2]. Solar cells are photovoltaic devices from a semiconductor that convert sunlight into a continuous electric current .These cells are a substitute for energy sources for terrestrial and space uses with low operating costs, and they do not cause any pollution[3]. Increasing the efficiency of the solar cell is important because there are several factors that improve the quantitative efficiency of solar cells by reducing the losses resulting from several effects, including the interaction of light with the cell material. Most semiconductors are characterized by high reflectivity of the electromagnetic wave, which can be reduced by the use of anti-reflection coating, which is one of the most important elements in the development of quantitative efficiency of solar cells [4].This technique depends on the phenomenon of interference in the thin films, where the reflected radiation suffers from differences in the paths and optical phases; therefore they overlap destructive interference and thus increase the proportion of the rays of the window. Anti-reflection coating is one of the key factors for the development of the efficiency of solar cells and for many optical devices operating within specific ranges of the electromagnetic spectrum, especially in the visible and infrared spectrum [5].An important factor in improving the efficiency of solar cells is the fact that the particle size of the materials used in the manufacture of solar cells is in the nanomaterials. The optical and electronic characteristics of the material change when one of its dimensions is within the Nanoscale dimension, which in turn exploits more than the electromagnetic spectrum [6].

Theoretical part

Quantitative efficiency of solar cells:

Quantitative efficiency is an important factor in solar cells, and (QE) is defined as the number of pairs (electron-gap) generated by each photon, and can be calculated using the following relationship [7].

$$QE = (1-R)\left[1-\frac{e^{\alpha w}}{(1+\alpha L_P)}\right] \quad \ldots\ldots (1)$$

Where:

(R) is a reflectivity.

(α) is a absorption coefficient.

(L_P) denotes to the Length of spread of small charge carriers in the region P.

(W) is the width of the Depletion region.

To calculate the quantity efficiency, you must find the following variables:

Calculation of the length of the minority shipment (L_p) in area P:

The propagation length of the minority load bearers for area P can be calculated through the following equation [8]:

$$L_P=\sqrt{D_P \tau_P} \quad \ldots\ldots (2)$$

Where:

D_p: Fixed deployment of area P and can be calculated after finding the values of the locomotor at the wavelength of the following equation [9]:

$$D_P = \frac{KT}{q}\mu_P \quad \ldots\ldots (3)$$

Where KT/q is the thermal voltages which equal (0.025 V) at room temperature (300 k°), q represents the electron charge, μ_p is the value of the area of the p and can be calculated from the following equation [8]:

$$\mu_P = \frac{e\tau_P}{m*} \quad \ldots (4)$$

Where:
(τ_p) is a Relaxation time for area P, (e)electron charge ,(m*) The effective mass of the electron.
The relaxation time is calculated from the following equation [10]:

$$\mathcal{T}_P = \frac{m^2 e^2}{20\varepsilon_r \hbar^3 N_\circ} \quad \ldots (5)$$

Where:
(m) Is the mass of Electron (9.1 x10^{-31} kg), (e) is an electron charge (1.6 x10^{-19}C), (ε_r) is the Dielectric constant [8], N_o is the focus in semiconductor which equals(10^{21}cm^{-3}) [11]. Dielectric constant values ε_r calculated from the following equation [12]:

$$\varepsilon_r = n^2 \quad \ldots (6)$$

n- Represents a refractive index

By compensating for equations (3), (5) and (6) in the equation (2), we get the value of the propagation length of the charge minority carriers for area P at the central wavelength.

Calculation of the depletion area width (W):

Calculation of the width of the depletion area for zone N, which is refered by the symbol (X_N):

We can calculate the width of the depletion region for area N using the following equation [13]:

$$X_N = \sqrt{\frac{2K_S\,\epsilon_\circ}{q}\frac{N_A}{N_D\cdot(N_A+N_D)}\,V_{bi}} \quad \ldots (7)$$

Calculation of the width of the depletion area for zone P that is refered by the symbol (X_P):

We can calculate the width of the depletion region for area P using the following equation [13]:

$$X_P = \sqrt{\frac{2K_S\,\epsilon_\circ}{q}\frac{N_D}{N_A\cdot(N_A+N_D)}\,V_{bi}} \quad \ldots (8)$$

From sections (1 and 2) we calculate the width of the total depletion area (W) by the following equation [13]:

$$W = X_N + X_P = \sqrt{\frac{2K_S\,\epsilon_\circ}{q}\frac{N_A+N_D}{N_A\cdot N_D}\,V_{bi}} \quad \ldots (9)$$

Where:

$N_A$is a negative ion concentration, N_D is a positive ionconcentration,ϵ_0 is a vacuum permittivity,K_s is a dielectric constant of material, q is charge of electron, V_{bi} is a built in voltage and can be calculated from the following equation [13]:

$$V_{bi} = \frac{KT}{q}\ln\frac{N_D * N_A}{n_i^2} \quad \ldots (10)$$

.n_i -concentration of free electrons in the semiconductor

Calculation of absorption factor (α):

The absorption coefficient define as the amount of decreasing energy from the incident radiation to the material due to the distance which has made towards the deployment of this wave within the semiconductor. The calculation of this ratio depends on the energy and the optical properties of the semiconductor, such as the amount of a power gap for the semiconductor material and the type of electronic transport that occurs between the valance band and the conductance band [14]. To calculate the absorption factor, we start by calculating the photon energy of the incident rays from the following equation [15]:

$$E = h\nu \quad \ldots (11)$$

The amount of this energy (T) is penetrated during the semi-conductive material and part of which (R) will be reflected. This penetrated part is given in accordance with the following equation [15].

$$T = (1 - R)^2 e^{-\alpha t} \quad \ldots (12)$$

To calculate the amount that the material (A) absorbs from these radiations, the following equation is adopted [15]:

$T = e^{-2.303\,A}$ …………………………………………………………………………………………… (13)

By equate the two relations (12)&(13)to get the equation:

$e^{-2.303A} = (1–R)^2 e^{-\alpha t}$ ……………………………………………………………………………… (14)

In the event that the amount absorbed by the material and the amount of it being carried out is approximately to one, that is, the amount of the substance is approaching zero and the equation (14) will be as the following:

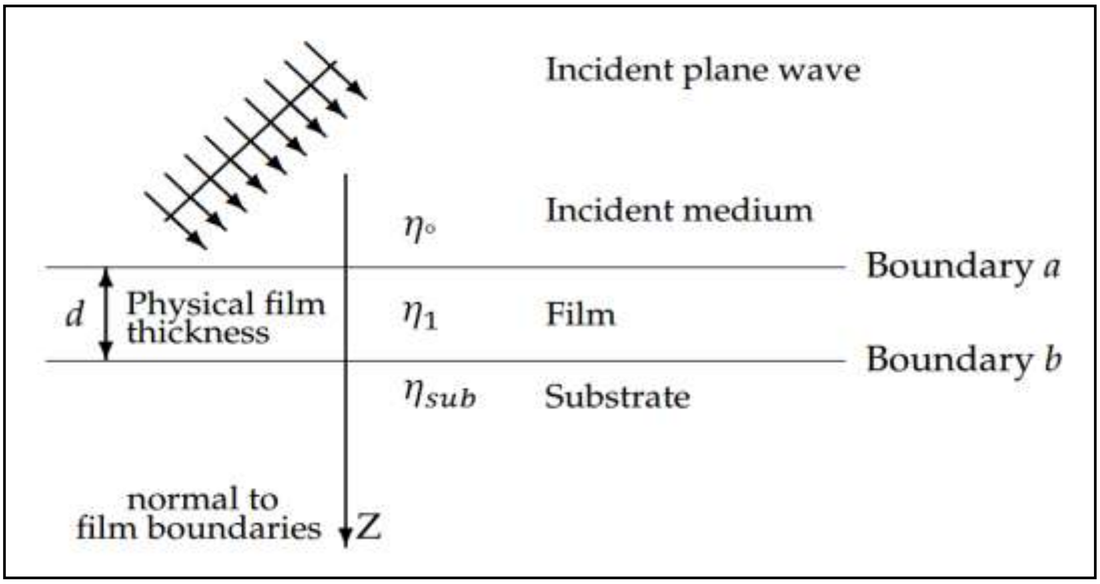
$e^{-2.303\,A} = e^{-\alpha t}$ ………………………………………………………………………………………(15)

And we can find the value of the absorption coefficient (α) from the equation:

$\alpha = 2.303\ (A/t)$ ……………………………………………………………………………..….. (16)

The Characteristic Matrix of Single Thin Film

The amount of reflectivity (R) is calculated for a single layer of thin film on the surface of a substance relying on the system of the Matrix and under this theory, each layer of the thin film can be represented by a square matrix type (2 x 2) to represent the properties of this layer [16].The distinctive matrix theory adopts the principle of multiple reflections of the incident wave on the thin film [17]. The thin film consist of two surfaces (a) upper (b) lower. The incident light at the borderline (a) suffers a reflection and the penetrative part is reflected at the threshold (b) and performs another, as shown in the figure below:



The Figure Shows a Low-level Wave on a Thin Film [18]

By applying the boundary condition for the electrical and magnetic fields of Maxwell equations to impose that the substances are not magnetic and by making mathematical simplifications we get the equation of the characteristic matrix which is given as follows:

$$\begin{bmatrix} Ea \\ Ha \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & i\sin\delta_1/\eta_1 \\ i\eta_1\sin\delta_1 & \cos\delta_1 \end{bmatrix} \begin{bmatrix} Eb \\ Hb \end{bmatrix}$$

Where:

is the First-class thickness, n_1 is the first- layer refractive coefficient δ_1

$$Ea\begin{bmatrix} 1 \\ Y \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & i\sin\delta_1/\eta_1 \\ i\eta_1\sin\delta_1 & \cos\delta_1 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_{sub} \end{bmatrix} Eb$$

Where:

Y- is the optical permittivity, η_{sub} is the Refractive index of the base material

$$Y = \frac{Ha}{Ea}$$

Or that

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & i\sin\delta_1 / \eta_1 \\ i\eta_1 \sin\delta_1 & \cos\delta_1 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_{sub} \end{bmatrix}$$

And for a system of which m number of layers, the equation is written as follows [19]

$$\begin{bmatrix} A \\ B \end{bmatrix} = \left\{ \prod_{r=1}^{m} \begin{bmatrix} \cos\delta_r & i\sin\delta_r / n_r \\ in_r \sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ n_{sub} \end{bmatrix}$$

Where:
m is a number of layers, $n_r$is refractive index ofa Layer r

The reflectivity (R) is given in the following equation[20].

$$R = \left(\frac{n_\circ B - C}{n_\circ B + C} \right) \left(\frac{n_\circ B - C}{n_\circ B + C} \right)^*$$

$B=E_a$ The sum of the electric field vehicle at the Borderline a.

$C=H_a$ The sum of the magnetic field vehicle is at the Borderline a.

Results and discussion

The proposed design of the coating (nano Ge) on a solar cell of the normal Silicon (Si/Si):(

The quantitative efficiency of a solar cell of the silicon was calculated without coating where the quantitative efficiency value was equal (QE = 68%), and its absorption factor ($1*10^4$ cm). The width of the depletion Area isequal to ($2x10^{-4}$ cm), and the length of the load bearers is L_P (3.6×10^{-4} cm) as well as the reflectivity R equals(30.2%) [2, 21] .

Figures-(1, 2) illustrate the reflectivity and quantum efficiency at the design wavelength(λ_0 = 550 nm) which consists of a single layer of anti-reflective coating of germanium with a quarter of the length of the design wavelength with a particle size varies within range (3.6-60 nm) on the solar cell of normal silicon (Si/Si) in case of vertical fall. In this design, we note that when the size of the paint particle is equal (Ps = 60 nm); It is of equal value (R = 34.32%) and the quantitative efficiency is (63.7407%), because the coating material at this size behaves in the normal state of the substance (Bulk Material). By decreasing the particle size of the coating material less than (60nm), the design reflectivity begins to decrease slightly as a result of the decrease in the coating refraction coefficient. When the radius of the r_{ps} coating is approaching from the radius of the Excition($\alpha°$), the refractive coefficient decreases as the particle size decreases dramatically ($Ps = 2r_{ps}$) and the effect of the coating layer on reflectivity is clearly shown. As we get the best design at (Ps = 4.4 nm).In which you can get less reflectivity (R = 0.1623%). The highest efficiency of the solar cell is worth (96.9004%) for the purpose of taking greater advantage of the electromagnetic radiation that is incident on it.After this volume, the coating refraction factor decreases significantly and approaches the refractive coefficient (n = 1) and the reflectivity of the substance basis for reduced effect of coating material on the incident plane wave, which leads to more reflective and less efficiency of the design quantity again, with a value of (73.9232%) at the particle size of the coating material (3.6 nm) to the coating refractive index is equal (1.08).

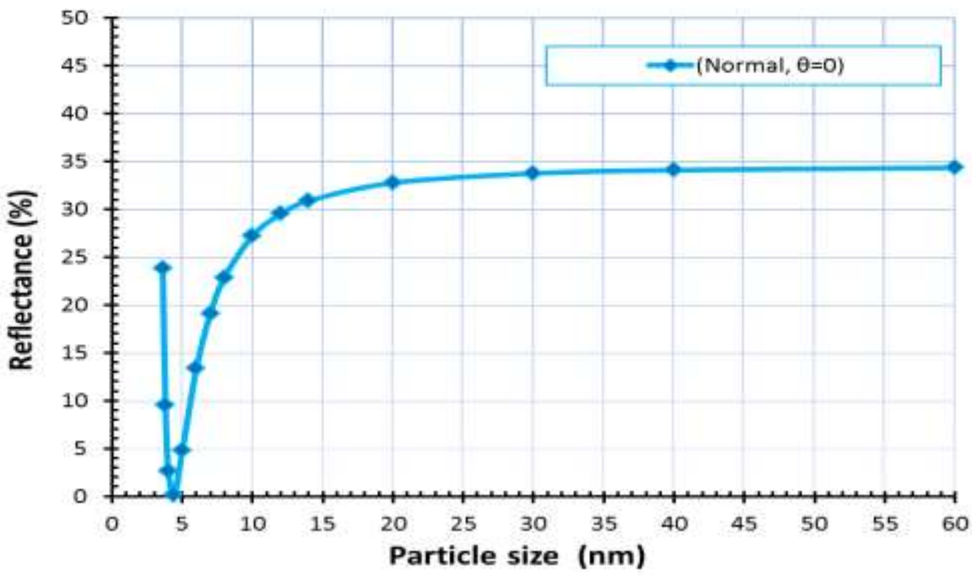


Figure 1- reflective design (Air/Nano Ge/(Si/Si) as a function of the particle size of the coating material, for the vertical fall, at the length of the design (λo = 550 nm),(L = 0.25 λo).

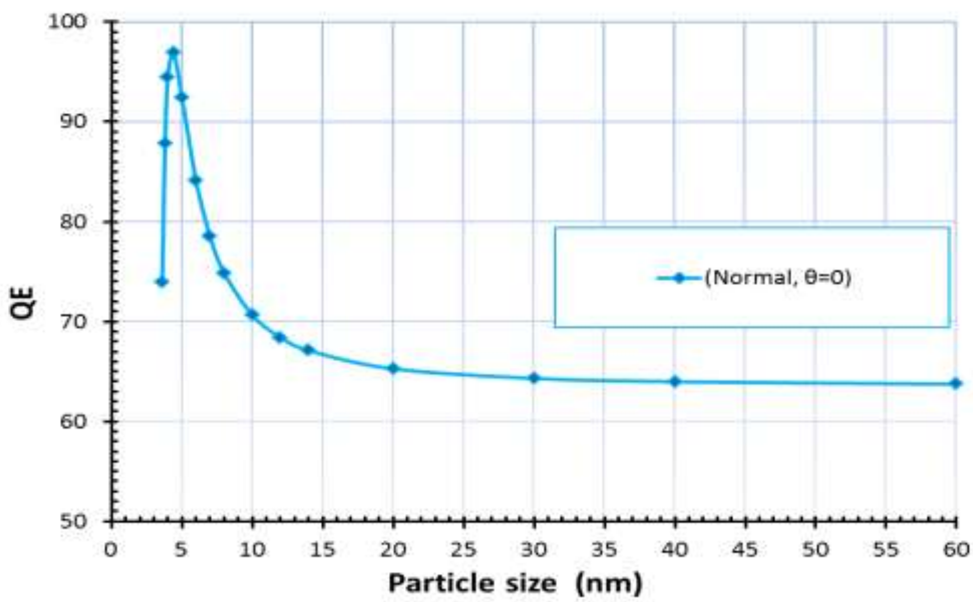


Figure 2- Quantity efficiency design (Air/Nano Ge/(Si/Si) as a function of the particle size of the coating material, for the vertical fall state, at the length of the design (λo = 550 nm), (L = 0.25 λo).

From previous data, it is clear that the lowest value of reflectivity at the thickness of the design wave equals (λ_o=550) nm, when the particle size of the coating material is equal to (4.4 nm). The highest value of quantitative efficiency at the same length as the design wave was when the size of the coating material is equal to (4.4 nm), so it can be suggested as an anti-reflective coating of the Si/Si solar cell.From previous data, it is clear that the lowest value of reflectivity at a wavelength can be studied the effect of the wavelength change (400-700nm) in the reflective and quantitative efficacy of the design chosen at incident angles (0) and (45) degrees.

Air/Nano Ge /(Si/Si) (Ps=4.4 nm, L=0.25λ_o, λ_o=550 nm

The effect of the wavelength change ((400-700nm) can be studied in the reflective and quantum efficiency of the design chosen at incident angles(0) and (45) degrees, the Figures (3-6) illustrate the change in the reflectivity values and the quantitative efficiency of the coating at the length of the design wave (λ_0 = 550 nm).Using the anti-reflective coating, we can get a zero reflectivity (R≈0) and the highest quantum efficiency at the length of the design. In the case of vertical fall, note that the value of reflective at the length of the design (λ_0 = 550 nm) is the least possible due to the verification of the BRAC condition(that the thickness of the paint is equal to a quarter of the design wave length) and this achieves the highest quantitative efficiency of design, at the larger and smaller wavelengths of the wavelength of the design wave, we note increased reflectivity and decreased quantitative efficiencies on both sides of the design wavelength as a result of the non-verification of the condition of the BRAC.At the larger and smaller wavelengths of the length of the design wave, we note increasing reflectivity and decreasing quantitative efficiency onboth sides of the design wavelength as a result of the failure to satisfy the BRAC condition. In the case of oblique fall at the angle (45 °), the effect of the polarization phenomenon can be seen on the reflected wave, where the increase in reflectivity can be observed at the vertical polarization pattern (S) and its decrease in the horizontal polarization (P) pattern.This is due to the different definition of the optical and optometry values of the middle of fall and penetration, the dependence of which is on the value of the angle of fall differently in both polarization. A side shift of reflectivity (R_s) and R_p can be observed in the direction of short wavelengths. This is because of the change in the optical thickness of the coating layer in the case of the oblique fall, which in turn depends on the coefficient effective refraction that changes with the angle of the fall and the pattern of polarization, As the angle of fall increases, the membrane appears to have less optical thickness, so that the central wavelength shifts to wavelengths shorter than the design wavelength ($\lambda_\circ$) [22].

Table 3- Effect of Change Angle of Fall on Reflective Design (Air/Nano Ge/(Si/Si)), at (Ps = 4.4), L=0.25λo),(λo=550 nm)

Quantity efficiency % of polarization pattern within design wavelength (λo=550 nm)		Reflectivity % of polarization pattern within design wavelength (λo=550 nm)		Incident angle (θ_o deg.)	No.
P	S	P	S		
96.9005	96.9005	0.1623	0.1623	0	1
96.3131	94.0545	0.7674	0.30945	45	2

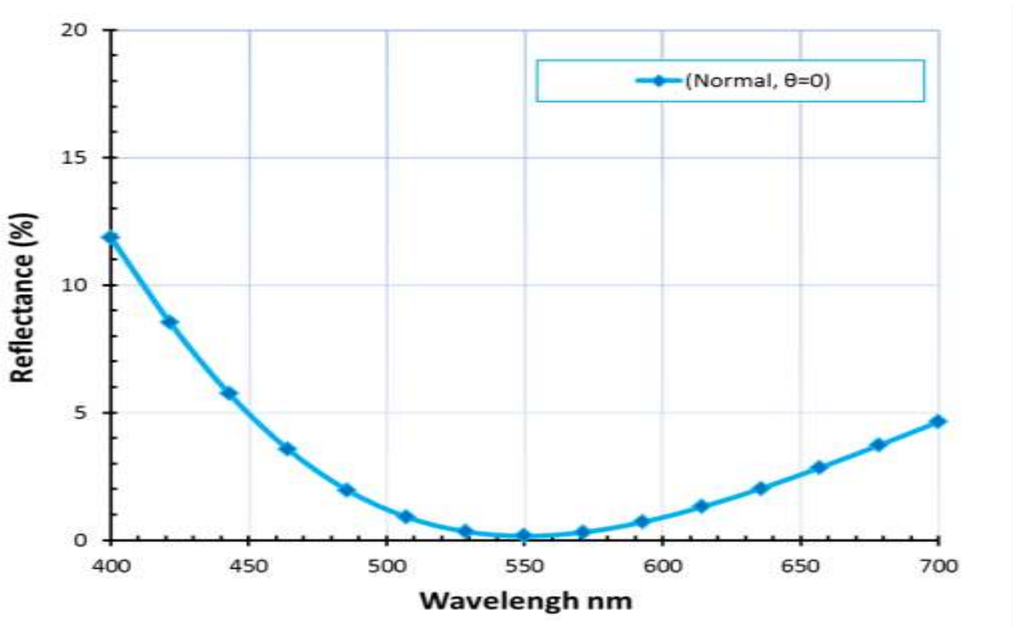


Figure 3- reflectivity as a function of the design wavelength (Air/Nano Ge/si/si) at the angle of (θ_o = 0^o)Ps =4.4 nm, L= $0.25\lambda_o$,λ_o=550 nm.

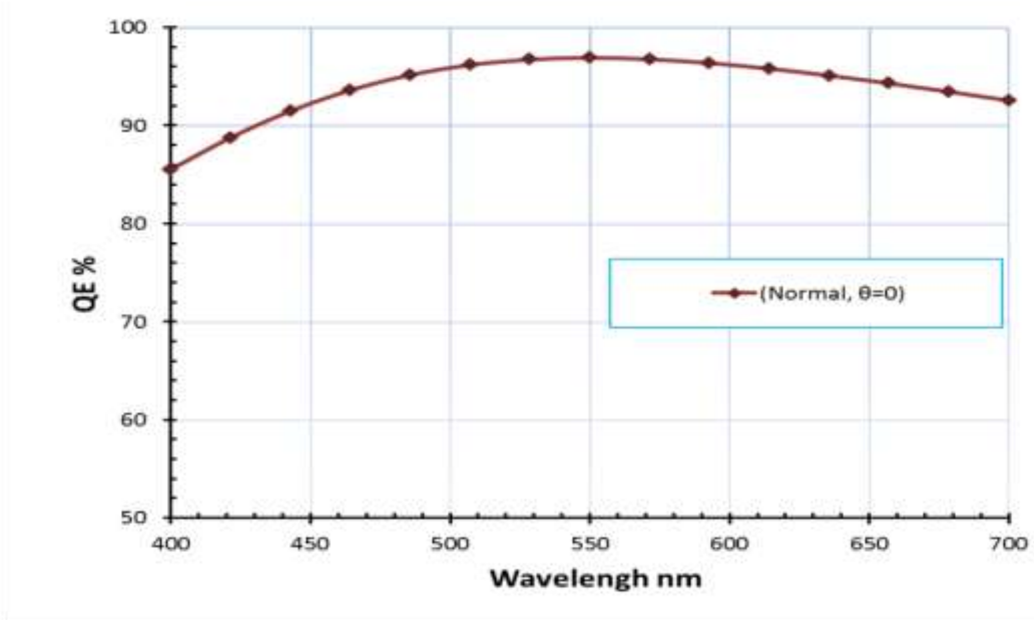


Figure 4- Quantitative Efficiency as a Function of the design Wavelength (Air/Nano Ge/si/si) at the Angle of (θ_o = 0^o)Ps =4.4 nm, L= $0.25\lambda_o$,λ_o=550 nm.

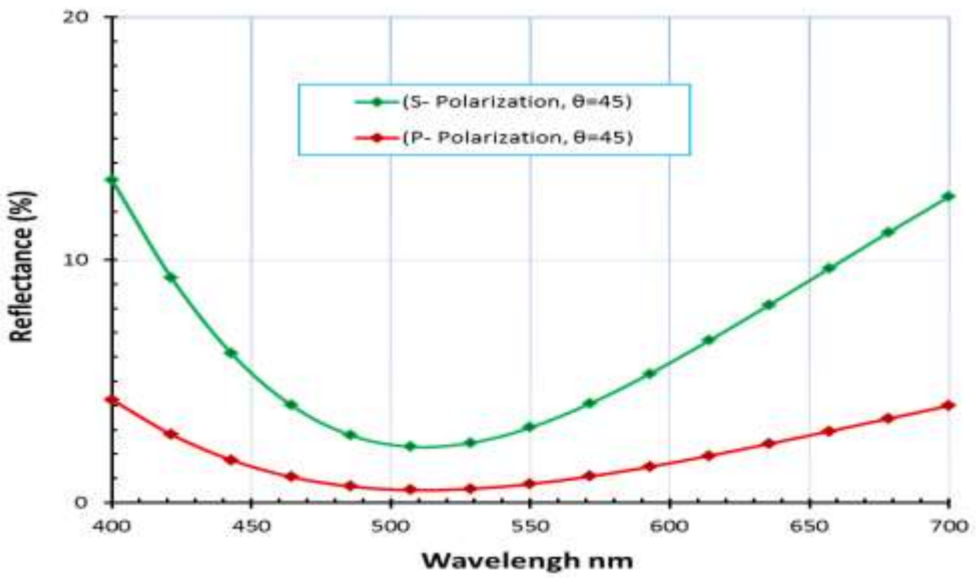


Figure 5- Reflective Wavelength as a Function for Design (Air/Nano Ge/(Si/Si) at the Angle of (θ_o = 45^o) Ps =4.4 nm, L= $0.25\lambda_o$,λ_o=550 nm.

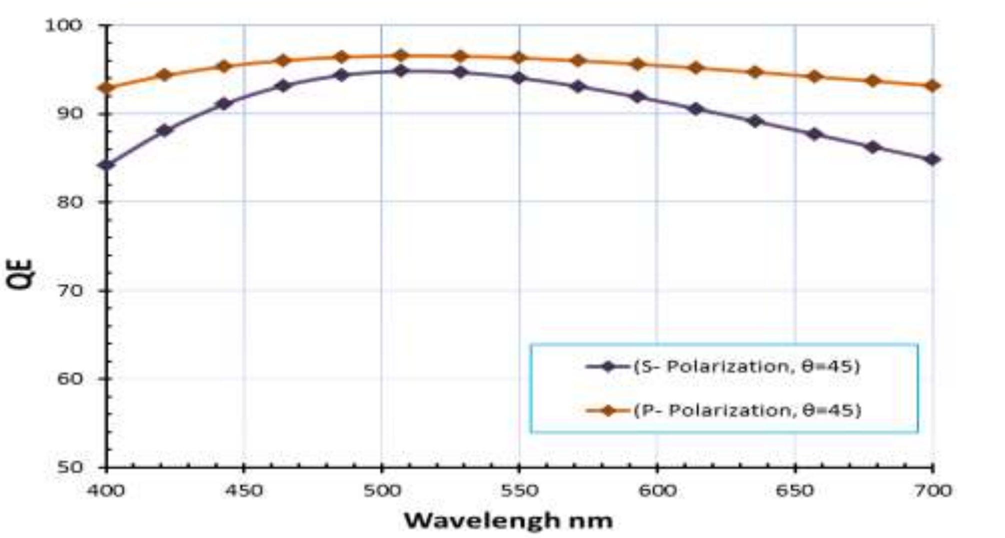


Figure 6- Quantitative Efficiency as a Function of the Wavelength fordesign (Air/Nano Ge/si/si) at the Angle of (θ_o = 45^o), Ps =4.4 nm, L= 0.25λ_o,λ_o=550 nm**.**

Conclusions

When a particle radius of the semiconductor material is equal to or smaller than the radius of the exciton, the optical properties of the material will change because of the effect of the quantum reservation. The energy gap of the substance is increasing and its Refraction coefficient decreases and reflectivity decreases with a reduction in Particle size.

The quantitative efficiency of solar cells is closely related to the reflective of the electromagnetic beam on its surface. The use of optical anti-reflective coatings on the surfaces of these cells, and the improvement of their optical properties through the control of the particle size of the coating, leads to the improvements of the efficiency Quantity Of those cells.

In the case of vertical fall and at the length of the design plane wave, the solar cell consisting of Silicon (Si/Si), it has been found that the highest efficiency of the amount (% 96.9004) was obtained for design (Air/nanoGe/(Si/Si)), when the particle size of the coating material is (Ps = 4.4 nm).

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