DOUBLE LAYER ANTIREFLECTION COATING DESIGN FOR CONDUCTIVE SOLAR CELLS

H. M. MOUSA¹, M. M. SHABAT²*, M. R. KARMOOT¹

¹ Al Azhar University, Physics Department, Gaza, Gaza Strip, Palestinian Authority
E-mail: H.mousa@alazhar-gaza.edu.ps
² Islamic University, Physics Department, Gaza, P.O. Box 108, Gaza Strip, Palestinian Authority
Corresponding author, E-mail: shabat@mail.iugaza.edu.ps

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Abstract. In this study, we have demonstrated the efficiency improvement of a four-layer structure solar cell model based on conductive nanoparticle materials. New artificial conductive nanoparticles have been used to optimize the efficiency of solar cells and to overcome some limitations of the efficiency of conventional solar cells structures. The antireflection coating structure has been proposed where conductive nanoparticles (CNPs) film layer and TiO₂ layer are sandwiched between a glass cover layer and a silicon substrate. The transmittance and reflectance are derived and computed by using the transfer matrix method and are obtained numerically for different values of unit cell sizes and gap widths of the CNPs. The nanoparticles dimensions have been adjusted leading to approximately 100% light transmission and the current density to be about 80 mA/cm².

Key words: thin-film solar cell, nanoparticles, transfer matrix method, absorption, reflection and quantum efficiency.

1. INTRODUCTION

Increasing global energy demand has dramatically attracted research and development of solar cell industry and technology [1–6]. Solar energy represents a clean energy source with high availability and simple implementation potential, providing a valuable mean to convert sunlight into electrical energy. The basic concept of solar cell efficiency depends on minimizing the light reflection or maximizing the transmission. This concept can be achieved through a process called antireflection coating (ARC) [7–20]. Various structures and materials have extensively been reported for both single ARC or double ARC through structures containing silicon materials and other semiconductor materials. There is a significant progress on ARC studies leading to an improvement in the cell efficiency. Most of the studies on ARCs focus on single-layer solar cells [1, 2]. But a single-layer antireflection coating is also known to be unable to cover a broad range of the solar spectrum [3, 4]. Recently, there has been an increasing consideration and interest in manufacturing solar cells based on nanoparticles and new artificial metamaterials. Modern ARCs based on nanoparticles have been investigated in order to achieve higher efficiencies and to overcome the limitations
of the conventional solar cells structure. More recently, solar cell layered structures based on conductive nanoparticles (CNPs) have been investigated for the first time, to the best of our knowledge, leading to a higher efficiency [21–22].

The electromagnetic effective medium theories have seen much renewed interest in the control of the effective electric permittivity or magnetic permeability of nanoparticles to be implemented in nanoparticles technology. Recently, Chung et al. [23] have introduced new materials based on CNPs by formulating a cubic array of conductive particles as an universal effective medium at visible and infrared frequencies and have predicted the relative electric permittivity \( \varepsilon_r \) and magnetic permeability \( \mu_r \) with good accuracy for the entire range of the particle sizes \( b \) and unit cell sizes \( a \).

We aim to use our simulation tools to numerically evaluate the potential of solar cells based on new artificial conductive nanoparticles by minimizing the reflection of a solar cell through the use of double layers antireflection coatings. The transfer matrix method (TMM) has been implemented taking into account the layered structure and the thicknesses of the layers forming the double layer ARCs. This paper is organized as follows. In Section 2, we present the simulation model and the corresponding theoretical framework. In Section 3, we give the detailed numerical results of our study. The conclusions and a brief discussion of the obtained results are provided in Section 4.

2. SIMULATION MODEL AND THEORY

Numerical simulations are used to build the solar cell structure model as shown in Fig. 1. The proposed solar cell model contains a four-layered structure. The basic layer here is a film of gold CNPs of thickness \( d_1 \). We analyze numerically the performance of silicon solar cell under the solar spectrum AM1.5 by incorporating the CNP layer and the TiO2 layer between a semi-infinite glass cover layer and a semi-infinite silicon substrate layer as a double layer ARC. The transmittance and reflectance are derived at various angles of transverse electric (TE) incidence and for different values of \( \varepsilon_r \) (different gap widths) at constant \( \mu_r \) and at constant \( \varepsilon_r \) for different values of \( \mu_r \) (different unit cell sizes) in visible and near-infrared radiation.

The nanoparticles film is deposited on a TiO2 film of thickness \( d_2 \), refractive index \( n_2 \) and covered by glass. The substrate is assumed to be silicon. Light is incident from glass onto the CNPs film. Figure 1 shows that both permittivity and permeability of CNPs film can be adjusted and controlled by some physical parameters of the CNPs (\( n_i = \sqrt{\varepsilon_r \mu_r} \) with [23]):

\[
\varepsilon_r = \varepsilon_0 \left[ \frac{1}{a^2} \left( \frac{b + 2b}{a} + \frac{2b}{a} \left( \frac{1}{a} \right) \right) \right], \\
\mu_r = \left( \frac{1 - b^2}{a^2} \right) \left( \frac{b}{a} \right), \\
b^2 = \left( \frac{\cosh \phi - 0.5}{\cosh \phi - 1} \right) (b - 2l_{sd} \tanh \phi)^2.
\]
Here $\varepsilon_h$ is the relative permittivity of the host dielectric material, $b$ is the particle size, $a$ is the unit cell size, $g$ is the gap between particles ($a = b + g$), $l_{SD}$ is the skin depth and $\phi = b / 2 \ l_{SD}$. As apparent from the model and the above relations, $\varepsilon_r$ can be tuned over a very wide range by varying the gap width $g$ and fixing the unit cell size $a$ below the skin depth ($a = 20 \ nm$), in this case $\mu_r = 1$, while $\mu_r$ can be independently tuned by varying $a$ at constant $g$ [23]. A beam of light undergoes reflection at $(i)$ and the transmitted portion undergoes another reflection at $(ii)$, $(iii)$.

We point out that $E_{i1}$, $E_{r1}$, $E_{t1}$, $E_{i2}$, $E_{r2}$, $E_{t2}$, $E_{i3}$, and $E_{r3}$, represent the sum of all incident, reflected, and transmitted fields at $(i)$, $(ii)$, $(iii)$, respectively. The optical parameters of the structure are studied using TMM, which relates the incident and reflected waves at the input layer with the incident and the reflected waves at the output layer [24–26].

The tangential components of the resultant electric and magnetic fields are continuous across the interface, that is

$$E_i = E_{i0} + E_{i1} = E_{i1} + E_{i1}$$

(1)

$$E_{i1} = E_{i2} + E_{r2} = E_{i2} + E_{i2}$$

(2)

$$E_{i3} = E_{i3} + E_{r3} = E_{i3}$$

(3)

$$B_t = B_0 \cos(\theta_0) - B_{t1} \cos(\theta_1) = B_{t1} \cos(\theta_1) - B_{t1} \cos(\theta_1)$$

(4)
\[ B_{ij} = B_{ij} \cos(\theta_i) - B_{ij} \cos(\theta_i) = B_{ij} \cos(\theta_i) - B_{ij} \cos(\theta_i) \quad (5) \]

\[ B_{iii} = B_{i3} \cos(\theta_i) - B_{i3} \cos(\theta_i) = B_{i3} \cos(\theta_i). \quad (6) \]

The electric and magnetic fields can be related by:

\[ B = \left( \frac{n}{c} \right) E = n \sqrt{\varepsilon_0 \mu_0} E, \]

where \( \varepsilon_0 \) and \( \mu_0 \) are the space permittivity and permeability, respectively:

\[ B_i = \gamma_0 (E_0 - E_{i1}) = \gamma_1 (E_{i1} - E_{ii}) \quad (7) \]

\[ B_0 = \gamma_1 (E_{i2} - E_{i2}) = \gamma_2 (E_{i2} - E_{i2}) \quad (8) \]

\[ B_{iii} = \gamma_2 (E_{i3} - E_{i3}) = \gamma_3 E_{i3}. \quad (9) \]

Here

\[ \gamma_0 = n_0 \sqrt{\varepsilon_0 \mu_0} \cos(\theta_i), \quad \gamma_1 = n_1 \sqrt{\varepsilon_0 \mu_0} \cos(\theta_i), \quad \gamma_2 = n_2 \sqrt{\varepsilon_0 \mu_0} \cos(\theta_i), \quad \gamma_3 = n_3 \sqrt{\varepsilon_0 \mu_0} \cos(\theta_i). \quad (10) \]

The phase differences are written as:

\[ \delta_1 = \left( \frac{2\pi}{\lambda_0} \right) n_1 d_1 \cos(\theta_i) \quad (11) \]

\[ \delta_2 = \left( \frac{2\pi}{\lambda_0} \right) n_2 d_2 \cos(\theta_i) \quad (12) \]

with \( \lambda_0 \) being the incident wavelength. Thus, we get

\[ E_{i2} = E_{i1} e^{-i\delta_1}, E_{i3} = E_{i2} e^{-i\delta_2}. \quad (13) \]

In the same way we get

\[ E_{i2} = E_{i1} e^{i\delta_1}, E_{i3} = E_{i2} e^{i\delta_2}. \quad (14) \]
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\[ E_{i} = E_{i1}e^{-i\delta_{1}} + E_{i2}e^{i\delta_{2}} = E_{i1} + E_{i2} \quad (15) \]
\[ B_{i} = \gamma_{1}(E_{i1}e^{-i\delta_{1}} - E_{i2}e^{i\delta_{2}}) = \gamma_{2}(E_{i1} - E_{i2}) \quad (16) \]

By aid of the equations written above we get the transfer matrix through the TE field equation as:

\[
\begin{pmatrix}
E_{ii} \\
B_{ii}
\end{pmatrix}
= \begin{pmatrix}
\cos(\delta_{1})\cos(\delta_{2}) - \gamma_{2}\sin(\delta_{1})\sin(\delta_{2}) & \frac{i\cos(\delta_{1})\sin(\delta_{2}) + i\sin(\delta_{1})\cos(\delta_{2})}{\gamma_{1}} \\
i\gamma_{1}\sin(\delta_{1})\cos(\delta_{2}) + i\gamma_{2}\sin(\delta_{1})\cos(\delta_{2}) & \cos(\delta_{1})\cos(\delta_{2}) - \frac{\gamma_{1}\sin(\delta_{1})\sin(\delta_{2})}{\gamma_{2}}
\end{pmatrix}
\begin{pmatrix}
E_{i} \\
B_{i}
\end{pmatrix}
\quad (17)
\]

The TE reflectance is given by:

\[ R = \frac{A_{i}^2 + B_{i}^2 + C_{i}^2 + D_{i}^2 - 2(AD_{i} + BC_{i})}{A_{i}^2 + B_{i}^2 + C_{i}^2 + D_{i}^2 + 2(AD_{i} + BC_{i})} \quad (18) \]

The transmittance is given by

\[ T = \frac{\mu_{0}n_{i}\cos(\theta_{0})}{\mu_{i}} \times \frac{4n_{0}\cos(\theta_{0})}{A_{i}^2 + B_{i}^2 + C_{i}^2 + D_{i}^2 + 2(AD_{i} + BC_{i})} \quad (19) \]

with

\[ A_{i} = n_{0}\cos(\theta_{0}) \left[ \cos(\delta_{1})\cos(\delta_{2}) - \frac{n_{0}\cos(\theta_{0})}{n_{i}\cos(\theta_{i})}\sin(\delta_{1})\sin(\delta_{2}) \right] \]
\[ B_{i} = n_{0}\cos(\theta_{0})n_{i}\cos(\theta_{i}) \left[ \frac{\cos(\delta_{1})\sin(\delta_{1})}{n_{0}\cos(\theta_{0})} - \frac{\sin(\delta_{1})\cos(\delta_{1})}{n_{i}\cos(\theta_{i})} \right] \]
\[ C_{i} = \left[ n_{0}\cos(\theta_{0})\sin(\delta_{1})\cos(\delta_{2}) + n_{i}\cos(\theta_{i})\sin(\delta_{1})\cos(\delta_{2}) \right] \]
\[ D_{i} = n_{0}\cos(\theta_{0}) \left[ \cos(\delta_{1})\cos(\delta_{2}) - \frac{n_{0}\cos(\theta_{0})}{n_{i}\cos(\theta_{i})}\sin(\delta_{1})\sin(\delta_{2}) \right]. \]

Here \( \mu_{0} \) is the permeability of silicon. The transfer matrix for the four layers in the case of the TM mode is:
The reflectance is given by:

\[
R = \frac{A_2^2 + B_2^2 + C_2^2 + D_2^2 - 2(A_2D_2 + B_2C_2)}{A_2^2 + B_2^2 + C_2^2 + D_2^2 + 2(A_2D_2 + B_2C_2)}, \tag{20}
\]

The transmittance is as follows:

\[
T = \frac{\varepsilon_0 n_0 \cos(\theta_0) \times [2n_0 \cos(\theta_0)]^2}{\varepsilon_0 n_0 \cos(\theta_0) \times A_2^2 + B_2^2 + C_2^2 + D_2^2 + 2(A_2D_2 + B_2C_2)}, \tag{21}
\]

with

\[
A_2 = n_0 \cos(\theta_0) \left[ \cos(\delta_1) \cos(\delta_2) - \frac{n_1 \cos(\theta_1)}{n_0 \cos(\theta_0)} \sin(\delta_1) \sin(\delta_2) \right],
\]

\[
B_2 = n_0 \cos(\theta_0) n_1 \cos(\theta) \left[ \cos(\theta_2) \cos(\delta_1) \sin(\delta_2) - \frac{\cos(\theta_1) \sin(\delta_1) \cos(\delta_2)}{n_1} \right],
\]

\[
C_2 = \left[ \frac{n_1 \sin(\delta_1) \cos(\delta_2)}{\cos(\theta_1)} + \frac{n_2 \sin(\delta_1) \cos(\delta_2)}{\cos(\theta_2)} \right],
\]

\[
D_2 = n_1 \cos(\theta_1) \left[ \cos(\delta_1) \cos(\delta_2) - \frac{n_1 \cos(\theta_1)}{n_2 \cos(\theta_2)} \sin(\delta_1) \sin(\delta_2) \right].
\] \tag{22}

The angle of refraction is related to the incidence angle \( \theta_0 \) by the Snell’s law as:

\[
n_0 \sin \theta_0 = n_1 \sin \theta_1 = n_2 \sin \theta_2 = n_i \sin \theta_i. \]

In order to compare the antireflection properties of different surface coatings, it is useful to evaluate the short circuit current \( J_{sc} \) \[27\], which is also a very important property in designing solar cells and can be calculated in the conventional approach as:

\[
J_{sc} = \frac{q}{h \nu} \int_{\lambda_{min}}^{\lambda_{max}} IQE(\lambda)(1 - R(\lambda))A \lambda AM_{1.5G}(\lambda)d\lambda, \tag{23}\]
where $h$ is Planck’s constant, $q$ is the electric charge, $c$ is the speed of light, $\lambda$ is the wavelength, $R(\lambda)$ is the measured reflectance, $AM_{1.5G}$ is the standard solar spectral irradiance $AM_{1.5G} = 1.5 \times 10^9 \text{W/m}^2$, and $\text{IQE}(\lambda)$ is the quantum efficiency of the solar cell. It is defined as the efficiency of carriers collected from the cell terminals relative to light transmitted through the front surface of the cell. For an ideal solar cell $\text{IQE}(\lambda) = 1$ for every wavelength.

3. NUMERICAL RESULTS AND DISCUSSION

In the solar cell models, our focus is how to obtain a minimum reflectance and a maximum transmittance in the visible light region. The optimum refractive indices for the layers composing the ARC materials, are determined based on the principles of quarter-wave films. For a double-layer ARC, the optimum refractive indices are found by $n_1 = \sqrt{n_0 n_s}$ and $n_2 = \sqrt{n_0 n_s}$ [5], where $n_0$ and $n_s$ are the refractive indices of the two layers surrounding the ARC, which in this case are glass at the top and silicon at the bottom, respectively. The refractive indices $n_1$ and $n_2$ correspond to the two materials forming the ARC, from top to bottom. We chose glass ($n_0 = 1.47$), silicon ($n_s = 3.77 - i0.012$), then $n_1$ is tuned to match $\sqrt{1.47^2 \times 3.77} = 2.1$ and $n_2 = \sqrt{1.47 \times 3.77^2} = 2.7$.

Equations (18)–(23), have been solved numerically to find out the reflectance, transmittance, and absorption of TE and TM polarization versus the incident wavelength for different incident angles, gap widths, cell sizes, and CNPs layer thicknesses.

Figure 2 illustrates the dependence of the reflected TE and TM waves on the incident wavelength for different values of incident angles ($\theta_0 = 0^\circ, 25^\circ, 50^\circ$). We note that, in the wavelength range $\lambda = 400–900$ nm, the TE reflectance increases to a maximum of (0.06, 0.07, 0.15) followed by a sharp drop to nearly 0 in the wavelength range $\lambda = 900–1200$ nm with the increase in angles of incidence of the previous values. For TM waves, we note that, in the wavelength range $\lambda = 300–1200$ nm, the reflectance increases rapidly to a maximum of (0.05, 0.135, 0.158), followed by sharp drop to nearly 0 with the decrease in angles of incidence of values ($\theta_0 = 50^\circ, 25^\circ, 0^\circ$). At $\theta_0 = 50^\circ$, the reflectance attains a maximum of 0.05 and the minimum is nearly 0. It is worth noting that $\theta_0 = 0^\circ$ is the preferred angle for the ARC process of TE waves while $\theta_0 = 50^\circ$ is the preferred angle for the ARC process of TM waves.
While transmittance’s peak of TE waves decreases to the values of $(0.98, 0.97, 0.95)$ for similar incidence range $(\theta = 0^\circ, 25^\circ, 50^\circ)$ in the wavelength range $(\lambda = 400 - 900 \text{ nm})$ and then heightens to $1$ in the wavelength range $(\lambda = 900 - 1200 \text{ nm})$, which means that no absorption is achieved for similar light wavelength and incidence range as indicated by Fig. 3. It is worth noting that $\theta_0 = 0^\circ$ is the perfect angle for the ARC process. The transmittance’s peak of TM waves increases to the values of $(0.989, 0.994, 0.998)$ for the previous incidence range. At $\theta_0 = 50^\circ$, the transmittance attains a maximum of $0.998$ and a minimum of $0.98$ in a wide wavelength of $\lambda = 400 - 1600 \text{ nm}$, which achieves the stability of high transmittance.
Fig. 3 – Transmittance ($T$) of TE and TM polarizations versus the wavelength ($\lambda$) for different incident angles and for $d_1 = 90$ nm, $d_2 = 50$ nm, $\mu = 1$, $g = 4$ nm, $a = 20$ nm, $b = 16$ nm, and $\varepsilon_r = 4.584$.

For comparison purposes, the influence of variation of the gap width on the reflection of TE and TM waves is presented in Fig. 4. At gap width of values (8, 6, 4) nm and unit cell size $a = 20$ nm, the particle length changes to the values (12, 14, 16) nm and the electric permittivity $\varepsilon_r$ of CNPs varies to the values of (1.972, 2.829, 4.584) and then, its refractive index $n_1$ changes very slightly to (1.404, 1.682, 2.141), respectively. We note that the TE reflectance increases when the gap width increases (decreases of $n_1$). If $g$ has the value 8 nm, the reflectance achieves a maximum of 0.189 and a minimum nearly 0.04. At $g = 6$ nm, the reflectance achieves a maximum of 0.179 and a minimum nearly 0. At $g = 4$ nm, the reflectance oscillates between a maximum of 0.07 and two minima of values (0.01, 0) at the wavelength range of $\lambda = 450 – 1200$ nm, which achieves the desired minimum reflectance. For TM waves, at $g = 4$ nm, the reflectance drops sharply from 0.05 to 0 and stabilizes at 0.015 in the wavelength range of $\lambda = 500 – 1200$ nm,
which achieves the desired minimum reflectance. At \( g = 4 \) nm, then \( n_1 = 2.14 \), the minimum reflectance spectra is achieved since \( n_1 \) is approximately near to the value \( \sqrt{n_1 n_s} = 2.1 \) and \( n_2 \) is near to the value \( \sqrt{n_2 n_s^2} = 2.7 \), which confirms the conditions of minimum reflectance that have been achieved by Saylan et al. [5]. It is worth stressing that our structure based on gold nanoparticles turned out to be a more efficient transmitter than the structure reported by Saylan et al. [5] since the optimized double-layer ARCs on GaAs_{0.69}P_{0.31}/Si can minimize the reflectance to below 5% within the spectral range of 400 – 945 nm while our structure lowers the reflectance to about 2% within the similar spectral range.

Figure 4 – Reflectance (R) of TE (\( \theta_t = 0^\circ \)), TM (\( \theta_t = 50^\circ \)) polarizations versus the wavelength (\( \lambda \)) for different gap widths \( g \) at \( d_1 = 90 \) nm, \( d_2 = 50 \) nm, \( \mu_r = 1 \), and \( a = 20 \) nm.

Figure 5 illustrates the transmittance of TE and TM waves versus the incident wavelength for different values of the gap width (\( g = 4, 6, 8 \)) nm. If \( g \) is held
constant at 4 nm, the TE transmittance peaks from 0.989 to 1 at the wavelength range of $\lambda = 600 – 1200$ nm, while the TM transmittance heightens to 0.985 at the wavelength range of $\lambda = 400 – 1200$ nm. This indicates that the value $g = 4$ nm improves the transmittance of the considered structure and the ARC process.

![Graph showing transmittance versus wavelength for TE and TM polarizations](image)

**Fig. 5** – Transmittance ($T$) of TE and TM polarizations versus the wavelength ($\lambda$) for different gap widths $g$ at $d_1 = 90$ nm, $d_2 = 50$ nm, $\mu_r = 1$, and $a = 20$ nm.

The reflectance versus the operating wavelength for several fixed values of the unit cell size $a = (300, 150, 50)$ nm of the CNPs layer is plotted in Fig. 6. Since $g = 0.1 \; a$, then $g$ changes to the values (30, 15, 5) nm and $b$ changes to the values (270, 135, 45) nm, respectively. At the cell size of (300, 150, 50) nm, the magnetic permeability $\mu_r$ reaches the values of (0.530, 0.728, 0.953) and the refractive index $n_1$ has the values of (3.527, 3.816, 4.367), respectively. As depicted in Fig. 6, the TE reflectance decreases by the increase of the unit cell size. The reflectance
oscillates between the values (0, 0.3) with \( a = 300 \text{ nm} \) in the wavelength range \( \lambda = (300 - 1200) \text{ nm} \). The maximum reflectance peaks to 0.3 at \( (a = 300 \text{ nm}, n_1 = 3.25) \), which is nearly high as compared to its values of \((0.16, g = 4 \text{ nm}, n_1 = 2.14)\) as observed in Fig. 4. This is because there is no matching between \( n_1 = 3.25 \) and \( \sqrt{n_0^2 n_1} = 2.1 \). In this case we can exchange TiO\(_2\) by other materials such as GaAs to get a minimum reflectance. The TM reflectance is also depicted in Fig. 6, at cell size of \((300, 150, 50) \text{ nm}\), where the CNPs may behaves as a dielectric. It shows reflectance’s value oscillation between \((0.02, 0.05), (0.06, 0.09), (0.06, 0.17)\), respectively, in a wide wavelength range of \( \lambda = 300 - 526 \text{ nm} \). As illustrated in Fig. 6, the reflectance decreases by increasing the unit cell size \( a \), and the minimum reflectance has been observed at \( \lambda = 358 \text{ nm} \) with \( a = 300 \text{ nm} \).

Fig. 6 – Reflectance (\( R \)) of the TE and TM waves versus the wavelength (\( \lambda \)) for different unit cell sizes \( a \) and for \( d_1 = 90 \text{ nm}, d_2 = 50 \text{ nm}, n_2=2.7, \) and \( \varepsilon_1 = 20 \).
Figure 7 displays the dependence of the TE and TM transmittance on the light wavelength for different unit cell sizes $a = (300, 150, 50) \text{ nm}$. It shows that the transmittance increases by increasing the unit cell size and that oscillates between the values 1 and 0.7 for TE waves at $a = 300 \text{ nm}$. The TM waves show a more stable transmittance of 0.98. The influence of $n_2$ on the ARCs is considered in Fig. 8. The reflectance against the operating wavelength for several values of the refractive index $n_2$, namely 2, 2.7, and 3.56, corresponding to Si$_3$N$_4$, TiO$_2$, and GaAs is plotted in Fig. 8. As illustrated in Fig. 8, the reflectance decreases when the refractive index increases, and the minimum reflectance of value 0.18 for the TE wave and of value 0.05 for the TM wave is observed if TiO$_2$ is replaced by GaAs since the refractive index of CNPs is $n_1 = 3.25$ at $a = 300 \text{ nm}$.

![Figure 7](image)

**Fig. 7** – Transmittance ($T$) of the TE and TM polarizations versus the wavelength ($\lambda$) for different unit cell sizes $a$ and for $d_1 = 90 \text{ nm}, d_2 = 50 \text{ nm}, n_2 = 2.7$, and $\varepsilon_r = 20$. 

![Figure 8](image)
Fig. 8 – Reflectance ($R$) of the TE and TM polarizations versus the wavelength ($\lambda$) for different values of the refractive indices $n_2$ and for $d_1 = 90$ nm, $d_2 = 50$ nm, and $\varepsilon_r = 20$.

Figure 9 displays the variation of the transmittance versus the wavelength for different values of $n_2 = (2, 2.7, 3.56)$ nm. It illustrates that the transmittance increases if the refractive index increases. The TE transmittance’s values oscillate between (0.82, 0.90) and the TM transmittance’s values oscillate between (0.95, 0.99) for $n_2 = 3.56$. The TM transmittance with GaAs is the best result. It is apparent that the TE transmittance is lower than the TM transmittance in the visible region since the existence of surface plasmon oscillations will create polarization charges that enhances the resonance between the frequency of the incident light
and the frequency of the plasmon oscillation. In this case, it is called dipole plasmon resonance. A high polarization and then a high electric field will increase the scattering of the incident light at the surface of the nanoparticles many times. As a result, its optical length increases and then it is transmitted and confined within the semiconductor resulting in a higher efficiency of the solar cell.

Fig. 9 – Transmittance (T) of the TE and TM polarizations versus the wavelength (λ) for different values of the refractive indices \( n_2 \) and for \( d_1 = 90 \) nm, \( d_2 = 50 \) nm, \( n_2 = 2.7 \), and \( \varepsilon_r = 20 \).

The current density (\( J_{sc} \)) is plotted versus the incidence angle for many thicknesses \( (d_1) \) of the CNP layer having the values (90, 150, 300) nm as shown in Fig. 10. An increase in the TE current density with the decrease in thickness can be noticed at normal incidence. At \( d_1 = 90 \) nm, the current density at \( \theta_0 = 0^\circ \) has the maximum value of 79.4 mA/cm\(^2\). As the thickness increases to the values of (150, 300) nm, the maximum values of current density at \( \theta_0 = 0^\circ \) changes to
(75.48, 77.99) mA/cm², respectively. As shown in Fig. 11, at $d_1 = 90$ nm, the TM current density increases to 82 mA/cm² when the incidence angle increases up to $50^\circ$ and drops to zero at $\theta_0 = 90^\circ$. It is obvious that the thickness $d_1 = 90$ nm is the preferred ARC thickness for the TM polarization.

![Graph 10](image1)

**Fig. 10** – Current density ($J_{sc}$) of TE polarization versus the angle ($\theta_0$) for different values of $d_1$ and for $d_2 = 50$ nm, $g = 4$ nm, $\mu_r = 1$, $\varepsilon_2 = 4.584$, $a = 20$ nm, $b = 16$ nm, and $n_1 = 2.14$.

![Graph 11](image2)

**Fig. 11** – Average TE and TM current density ($J_{sc}$) versus the angle ($\theta_0$) for $d_2 = 50$ nm, $g = 4$ nm, $\mu_r = 1$, $a = 20$ nm, and $d_1 = 90$ nm.

### 4. CONCLUSION

In this paper we have modeled the optimal refractive indices values for double layer antireflection coatings for minimization of reflectivity losses at the silicon surface. We have also presented in some detail an efficient approach to
optimize the reflectance and transmittance for TE and TM polarized incident light through CNPs structure. It was found that the antireflection effect of CNPs/TiO₂ double-layer ARC is more operative in ARCs process than that of single layer CNPs. It is apparent that the TE transmittance is lower than the TM transmittance in the visible region because a dipole plasmon resonance is generated at the surface of CNPs in the TM case. Moreover, our structure based on gold nanoparticles turned out to be an efficient transmitter than that studied in Ref. [5] since our structure can minimizes reflectance to about 2%. This confirms that gold nanoparticles are more effective in the antireflection coatings process. The results reported in this study can be used as a significant tool for efficiency improvement in thin film silicon solar cells.

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