Design of an Antireflection Coating for Mid- wave Infrared Regions in the Range (3000-5000) nm

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ABSTRACT
This work includes a theoretical study to design antireflection coating for mid-infrared region of electromagnetic spectrum depending on characteristic matrix method using silicon (Si) as a substrate in order to coated by using Zinc Sulfide (ZnS) and Cadmium Sulfide (CdS) as a low and high coating material respectively. The results shows that, for the normal incidence, the reflectance of silicon reduced from (30.31) to (0.00049) when coated by three layer according to the design [Air/LHL/Si]. Also the effect of angle of incidence on the reflectance spectrum of this design are investigate. The results shows that the reflectance are increases with shifting toward shorter wavelengths.

Keywords: Thin Films, Optical coatings , Antireflection Coating**.**

1. INTRODUCTION
The principle of the single and multilayer antireflection coatings is based on the destructive interference of light reflected from the interfaces of the coating layers. Thus, the AR coatings should exhibit a reflective index between those of air and substrate [1,2]. Antireflection coating is required for infrared optics in order to increase transmission for use in high indexed IR optics materials [3]. Single layer AR coatings normally can cover only very narrow bandwidth. Therefore, a V-shape reflection performance curve results from the use of this coating. In order to achieve broad band optical performance, a multilayer stack is usually necessary [4]. Reflective and antireflective (AR) optical coatings have been developed for a variety of applications, e.g., for optical and electro-optical systems in telecommunications, medicine, military products and consumer products. AR coatings have been widely used in glass lenses, eyeglasses, lasers, mirrors, solar cells, IR diodes, multipurpose broad and narrow band-pass filters, architectural and automotive glass and displays such as cathode ray tubes, as well as plasma, liquid crystal and flat panel displays [5]. In high power lasers, it is very important to reduce the optical reflective losses and accommodate the highest possible power densities on all components. So, it is necessary to use various anti-reflective films in lasers components [6]. Zinc sulphide's transmission spectrum from 0.4 µm to 11 µm is free from major absorption, with the material easily available in large quantity and high purity to suit for most electro optical applications [7,8]. Silicon is a semiconductor optical material with relatively high refractive index. It is used in infrared devices as windows, lenses and transmission filters. The high reflection index of silicon causes important reflection loss from its surface, even in thin film form. Therefore, its surface should be coated with an antireflection coating to reduce the reflectance or to increase the transmittance[2]. Solar cells have a number of losses mechanisms, all of which can be minimized. Optical losses arise from reflection at the semiconductor surface and they can be reduced by surface texturing and depositing of antireflection coatings. The surface texturing, which bends incoming rays into a more horizontal direction and thus increase their path length inside the silicon [9]. Antireflection coating deposited on the surface is one of the most important methods for reducing the reflection loss of silicon solar cells [10].

2. THEORETICAL BASIS
When plane electromagnetic wave is normal incident to the surface, the amplitude of the reflected wave at the interface between the substrate and the incident media is proportional to the Fresnel amplitude reflection coefficient , r ;

$$ r = \left(\frac{n_o - n_s}{n_o + n_s}\right) \quad \ldots\ldots (1) $$

where n_o is the refractive index of the incident medium (usually air), and n_s is the refractive index of the substrate. The reflectance R, given by[12]:

$$ R = r\,r^* = |\,r\,|^2 $$
$$ R = \left(\frac{n_o - n_s}{n_o + n_s}\right)\left(\frac{n_o - n_s}{n + n_s}\right)^* \quad \ldots\ldots (2) $$

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Characteristic matrices are usually used to calculate the reflectance of an assembly of thin film layers. each layer is represented by a 2×2 matrix M, of the form:

$$M_j = \begin{pmatrix} \cos\delta_j & (i\sin\delta_j)/\eta_j \\ i\eta_j\sin\delta_j & \cos\delta_j \end{pmatrix} \quad \ldots\ldots(3)$$

where ηj is the effective refractive index of the layer and δj is its phase thickness given by:

$$\delta_j = 2\pi n\, d_j /\lambda \quad \ldots\ldots(4)$$

dj - physical thickness of the layer.

For a general case of assembly of layers, the characteristic matrix is simply the product of the individual matrices taken in the correct order and is denoted by N [11]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{r=1}^{N} \begin{bmatrix} \cos\delta_r & i\sin\delta_r/\eta_r \\ i\eta_r\sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_{sub} \end{bmatrix} \quad \ldots\ldots\ldots (5)$$

$$\eta_r = y\cos\theta \quad \text{for } s-\text{polarization} \quad \text{and} \quad \eta_r = \frac{y}{\cos\theta} \quad \text{for } P-\text{polarization}$$

B and C are the total electric and magnetic field amplitudes. The reflectivity of an assembly of thin films is calculated through the concept of the optical admittance. The multilayer can be replaced by a single surface, which has an input optical admittance Y given by:

$$Y = B / C \quad \ldots\ldots(6)$$

Y is the admittance presented to the incident wave by the coating. The admittance presented by simple interface between two media is indistinguishable from the reflectance at that interface. This concept is used to calculate the reflectance of an assembly of thin films and the transmittance and be derived through the relationship of T=(1-R). The expressions for reflectance, transmittance and phase changes on reflection are given respectively as follows:

$$R = \left(\frac{\eta_o B - C}{\eta_o B + C}\right) \left(\frac{\eta_o B - C}{\eta_o B + C}\right)^* \quad \text{and} \quad T = \frac{4\eta_o \, \text{Re}(\eta_{sub})}{(\eta_o B + C)(\eta_o B + C)^*} \quad \ldots\ldots(7)$$

3. DESIGN OF ANTIREFLECTING COATING

The design of thin-film multilayer coating often specifies the transmittance and reflectance values at a number of wavelengths, angles, and polarizations of the incident light. At first we determine the materials which using to design antireflection coating. For single layer an antireflection coating, the material used to deposit an antireflection coating must have a refractive index equal $n=(n_o \times n_s)^{1/2}$, where n_s is the refractive index of the substrate [6]. Silicon (Si) using as a substrate. For the normal incidence, the reflectance of Si as a function of wavelength are shown in figure (1). It clear that the reflectance is high (R~30.31 %). ZnS and CdS using as low and high index coating materials. In this section, five theoretical designs of antireflection coating have been suggested. each design have a different number of layer or different arrangement of the layers from the others in order to minimize the reflectance of silicon. Figure (2-6) shows the reflectance as a function of wavelength at normal incidence for the five design, the design [Air / LHL /Si] have minimum reflectance (high transmittance) in design wavelength. So, we using this design to study the effect of angle of incident on the performance of this design. Figure (7-11) shows the effect of angle of incident on the reflectance as a function of wavelength of the design [Air / LHL /Si]. When angle of incidence increase the reflectance increase with shift toward shorter wavelengths, this shift may be as result of varying the optical thickness of layer due to the oblique incidence of plane electromagnetic wave.
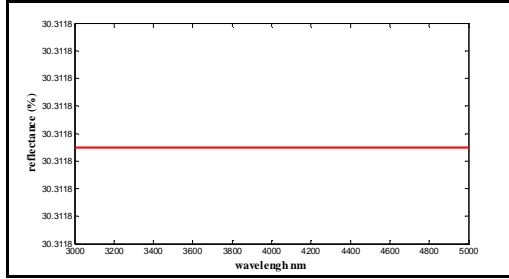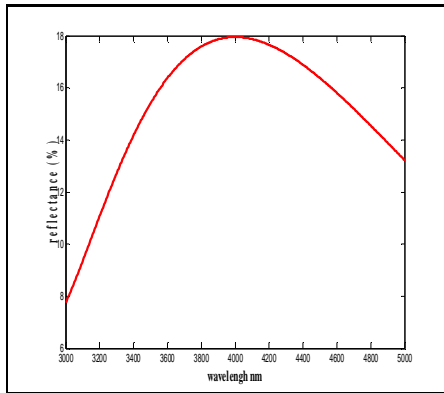
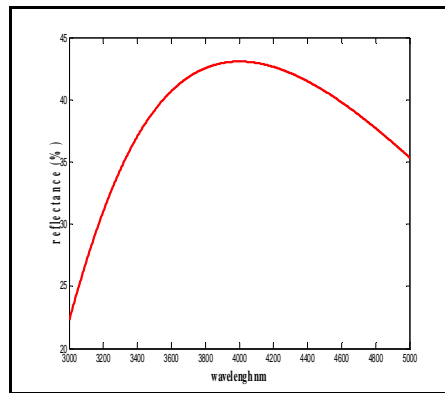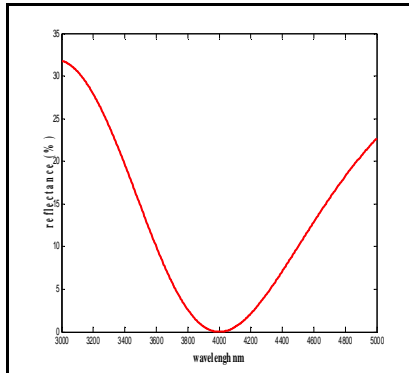**Figure 1:** Reflectance as a function of wavelength of Silicon from air.
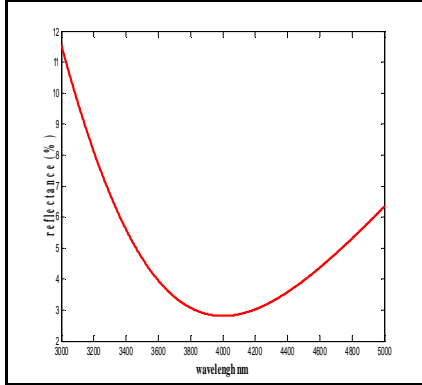
Figure 2: Reflectance as a function of wavelength of the design Air / L /Si, n_L =2.2, n_{sub}=3.45 , λ_o=4000 nm, normal incidence (θ_o=0˚)
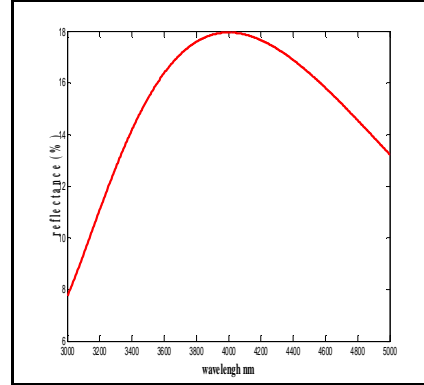
Figure 3: Reflectance as a function of wavelength of the design Air / H /Si , n_L =2.2, n_{sub}=3.45 λ_o= 4000 nm, normal incidence (θ_o=0˚)

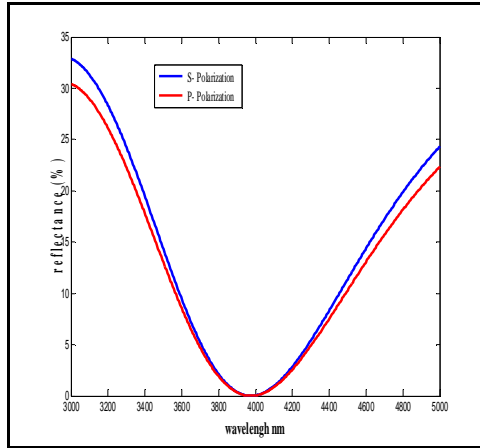
Figure 4: Reflectance as a function of wavelength of the design Air / LH /Si, n_L =2.2, n_{sub}=3.45 , n_H =2.6λ_o=4000 nm, normal incidence (θ_o=0˚)

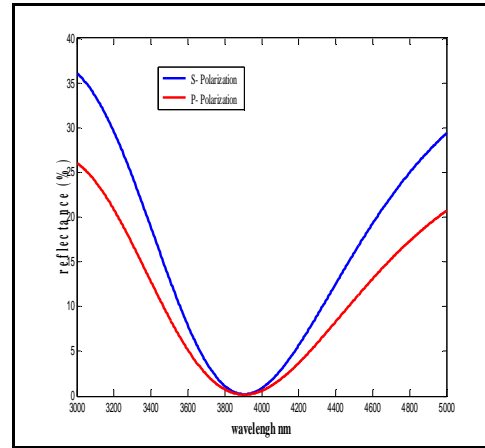**Figure 5:** Reflectance as a function of wavelength of the design Air / HL /Si , n_L =2.2, n_H =2.6 n_{sub}=3.45, λ_o=4000 nm, normal incidence (θ_o=0˚)

Figure 6: Reflectance as a function of wavelength of the design Air / LHL /Si , n_L =2.2, n_H =2.6 n_{sub}=3.45, λ_o=4000 nm, normal incidence (θ_o=0˚)

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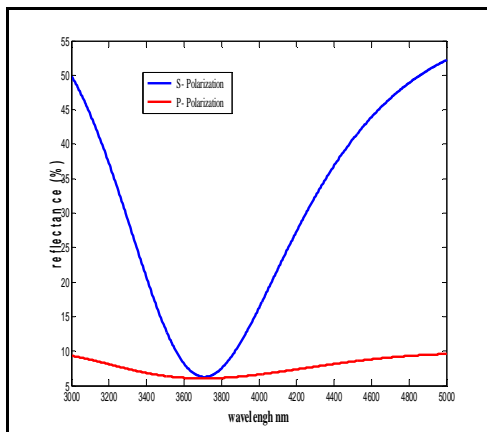
Figure 7: Reflectance as a function of wavelength of the design Air / LHL /Si, n_L =2.2, n_H =2.6 , n_{sub}=3.45, λ_o=4000 nm, oblique incidence (θ_o=15°)

Figure 8: Reflectance as a function of wavelength of the design Air /LHL /Si , n_L =2.2, n_H =2.6 n_{sub}=3.45, λ_o=4000 nm, oblique incidence (θ_o=30)
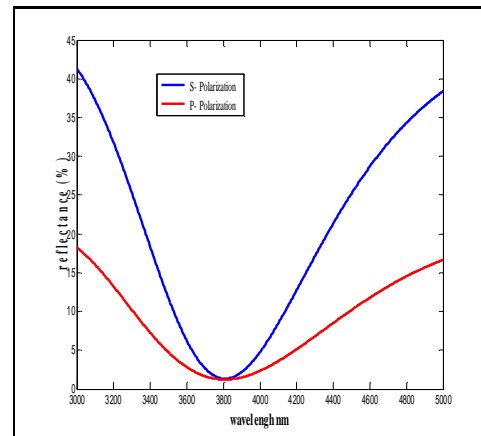

Figure 9: Reflectance as a function of wavelength of the design Air / LHL /Si , n_L =2.2 , n_H =2.6, n_{sub}=3.45, λ_o=4000 nm, oblique incidence (θ_o=45°)
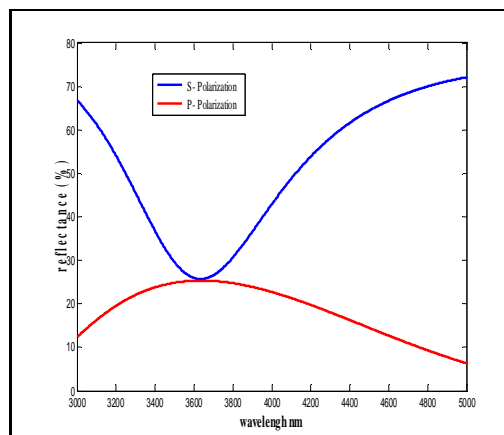

Figure 10: Reflectance as a function of wavelength of the design Air / LHL /Si , n_L =2.2, n_H =2.6, n_{sub}=3.45, λ_o=4000 nm, oblique incidence (θ_o=60)

Figure 11: Reflectance as a function of wavelength of the design Air / LHL /Si , n_L =2.2, n_H =2.6 n_{sub}=3.45, λ_o=4000 nm, oblique incidence (θ_o=75°)

Table (1) shows the value of reflectance of the design [Air / LHL /Si] for TE and TM modes due to the varying angle of incidence. It is clear that the reflectance increases as the angle of incidence increase and the increase in reflectance for TE- mode (S- Polarization) is larger than the reflectance for TM- mode (P- Polarization).

Table 1: Varying effect angle of incidence on the design **Air / LHL /Si**

No.	Angle of incidence (deg.)	Reflectance at (λ_o=4000 nm)		Minimum Reflectance	
		S- Polarization	P- Polarization	S- Polarization	P- Polarization
1	0	0.0004	0.0004	0.0004	0.0004
2	15	0.042	0.055	0.0145 at (λ_o=3976 nm)	0.005 at (λ_o=3976 nm)
3	30	0.880	0.594	0.2047 at (λ_o=3904nm)	0.1665 at (λ_o=3904 nm)
4	45	4.774	2.342	1.325 at (λ_o=3808 nm)	1.226 at (λ_o=3808 nm)
5	60	16.27	6.605	6.257 at (λ_o=3708 nm)	6.045 at (λ_o=3708 nm)
6	75	42.93	22.73	25.7 at (λ_o=3636 nm)	25.36 at (λ_o=3636 nm)

4.CONCLUSION

The results obtained from this work are essential in the design of antireflection coating for solar cells application to minimize the reflectance of solar radiation. By using antireflection coating, the reflectance of silicon were minimized from 30.31 % to 0.00049 by using the design [Air/LHL/Si]. Also the results shows that, when the incident angle of radiation increase the reflectance increase for both TE- mode (S- Polarization) and TM- mode (P- Polarization) due to oblique incidence which leads to varying in optical thickness of layers of suggested design with shifting to the reflectance spectrum toward shorter wavelength region.

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