EFFECT OF SOLAR CELL SURFACE COATING

ON

CONVERSION EFFICIENCY

BY

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ABSTRACT :

The paper illustrates the use of antireflecting layers for coating solar cell surface in order to improve the conversion efficiency. These coatings may be in single or multilayer. Mathematical analysis are given to determine the reflection losses in both cases .

Through numerical application, by the use of computer programming, and regarding the economical point of view a comparison is made between the conversion efficiency for solar cells with and without antireflection coatings.

INTRODUCTION :

To improve the conversion efficiency of solar cells, the different conversion losses must be reduced as much as possible. Coating the solar cell surface with materials having intermediate reflection coefficient between the air and the solar cell material has considerable effect on the reduction of reflection losses. Also the multiplication of antireflection layers the conversion efficiency .

The materials used for single-layer cell surface coating usually are MgF_2 , SiO_2 , Al_2O_3 , Sio and CeO_2 (Ref. 2) . Acomparicon between these materials is illustrated through the numerical application given later. With respect to couble- layer antireflection coatings, the first layer can be made from MgF_2 or LiF of SiO_2 and the second layer is usually made from TiO_2 with thickness 0.045 microns. For triple - layer antireflection coating, the first layer materials are usu[illegible] or SiO_2 , the second layer is made from $ZrSiO_4$, wit[illegible] microns and the third layer is usually ma[illegible] thickness 0.048 microns .

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Vol., 5, No . 1 , June 1980 .

. MATHEMATICAL FORMULATION :

The reflection loss using a multi- layer antireflection coatings (Ref. 3) is given by :

$$R = \left| \frac{a}{b} \right|^2 \qquad \ldots\ldots\ (1)$$

where :

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} N_o & -1 \\ N_o & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos \delta_k & j\frac{\sin \delta_k}{N_k} \\ jN_k \cdot \sin \delta_k & \cos \delta_k \end{bmatrix} \cdot \begin{bmatrix} 1 \\ N_s \end{bmatrix} \ldots\ (2)$$

and

$$\delta_k = \frac{2\pi}{\lambda} N_k \cdot t_k \qquad \ldots\ldots\ (3)$$

where :

N_o is the refractive index of the air,
N_k is the refractive index of the K th coating layer,
N_s is the refractive index of the solar cell material,
t_k is the thickness of the K th coating layer
& λ is the wave length of the incident light.

1- Single - layer Antireflection coating :

Coating the solar cell with a single - layer antrireflection coating of material , whose refractive index, N_1 , and thickness, t_1. The phase difference introduced by two consequtive reflection, δ_1, on cell with refractive index, N_2 . The reflection loss can be obtained from eqs (1,2,3) as

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} N_o & -1 \\ N_o & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos \delta_1 & j\frac{\sin \delta_1}{N_1} \\ jN_1 \cdot \sin \delta_1 & \cos \delta_1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ N_2 \end{bmatrix}$$

where :

$$\delta_1 = \frac{2\pi}{\lambda} N_1 \cdot t_1 \qquad \ldots\ldots\ (4)$$

Therfore,

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} (N_o - N_2).\cos\delta_1 + j\left(\frac{N_o N_2}{N_1} - N_1\right).\sin\delta_1 \\ (N_o + N_2).\cos\delta_1 + j\left(\frac{N_o N_2}{N_1} + N_1\right).\sin\delta_1 \end{bmatrix} \quad ..(5)$$

If :

$$A = (N_o - N_2) . \cos\delta_1 \; , \qquad ..... (6a)$$

$$B = \left(\frac{N_o N_2}{N_1} + N_1\right). \sin\delta_1 \; , \qquad ..... (6b)$$

$$C = (N_o + N_2) . \cos\delta_1 \qquad ..... (6c)$$

&

$$D = \left(\frac{N_o N_2}{N_1} + N_1\right). \sin\delta_1 \qquad ..... (6d)$$

so,

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} A + jB \\ C + jD \end{bmatrix} \qquad ...... (7)$$

and from eq s (1,7), the reflection loss for a single-layer antireflection coating is

$$R = \frac{A^2 + B^2}{C^2 + D^2} \qquad .... (8)$$

2-Double - layer Antireflection Coating :

This system consists of two layer, the first layer is met by the air , whose refractive index, N_1, and thickness, t_1, the second layer is attached to the solar cell surface, whose refractive index, N_2, and thicknessn, t_2, The refractive index of the solar cell is N_3. The reflection loss expression for double-layer antirefledtion coatings can be obtained from eq s (1,2;3) as

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} N_o & -1 \\ N_o & 1 \end{bmatrix} . \begin{bmatrix} \cos\;_1 & j\frac{\sin\;_1}{N_1} \\ jN_1.\sin\;_1 & \cos\;_1 \end{bmatrix} . \begin{bmatrix} \cos\;_2 & j\frac{\sin\;_2}{N_2} \\ jN_2.\sin\;_2 & \cos\;_2 \end{bmatrix} . \begin{bmatrix} 1 \\ N_3 \end{bmatrix}$$

where :

$$\delta_1 = \frac{2\pi}{\lambda} N_1 . t_1 \qquad \ldots\ldots (9a)$$

and

$$\delta_2 = \frac{2\pi}{\lambda} N_2 . t_2 \qquad \ldots\ldots (9b)$$

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \left[(N_o - N_3).\cos\delta_1 . \cos\delta_2 + \left(\frac{N_1 . N_3}{N_2} - \frac{N_o . N_2}{N_1}\right).\sin\delta_1 . \sin\delta_2 \right] \\ + j\left[\left(\frac{N_o . N_3}{N_2} - N_2\right).\cos\delta_1 . \sin\delta_2 + \left(\frac{N_o . N_3}{N_1} - N_1\right).\sin\delta_1 . \cos\delta_2 \right] \\ \left[(N_o + N_3).\cos\delta_1 . \cos\delta_2 - \left(\frac{N_1 . N_3}{N_2} + \frac{N_o . N_2}{N_1}\right).\sin\delta_1 . \sin\delta_2 \right] \\ + j\left[\left(\frac{N_o . N_3}{N_2} + N_2\right).\cos\delta_1 . \sin\delta_2 + \left(\frac{N_o . N_3}{N_1} + N_1\right).\sin\delta_1 . \cos\delta_2 \right] \end{bmatrix} \qquad \ldots\ldots (10)$$

If :

$$A = N_o - N_3 \quad , \quad B = \frac{N_1 . N_3}{N_2} - \frac{N_o . N_2}{N_1} ,$$

$$C = \frac{N_o . N_3}{N_2} - N_2 \quad , \quad D = \frac{N_o . N_3}{N_1} - N_1 ,$$

$$E = N_o + N_3 \quad , \quad F = \frac{N_1 . N_3}{N_2} + \frac{N_o . N_2}{N_1} ,$$

$$G = \frac{N_o . N_3}{N_2} + N_2 \quad , \quad H = \frac{N_o . N_3}{N_1} + N_1 ,$$

$I = \cos\delta_1 \cdot \cos\delta_2$, $J = \sin\delta_1 \cdot \sin\delta_2$,

$K = \cos\delta_1 \cdot \sin\delta_2$ & $L = \sin\delta_1 \cdot \cos\delta_2$.

So, the reflection loss for a double - layer antireflection coating is :

$$R = \frac{(A.I + B.J)^2 + (C.K + D.L)^2}{(E.I - F.J)^2 + (G.K + H.L)^2} \qquad \text{........ (11)}$$

3- Triple - layer Antireflection Coating :

This system consists of three layers. The first layer is met by the air, whose refractive index, N_1, and thickness, t_1. The second is medium between the first and the third, whose refractive index, N_2, and thickness, t_2. The third is attached to the solar cell surface, whose refractive index, N_3, and thickness, t_3.

If :

N_o is the refractive index of the air

&

N_4 is the refractive index of the solar cell .

So, the reflection loss expression for triple - layer antireflection coatings can be obtained as

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} N_o & -1 \\ N_o & 1 \end{bmatrix} \begin{bmatrix} \cos\delta_1 & j\frac{\sin\delta_1}{N_1} \\ jN_1 \cdot \sin\delta_1 & \cos\delta_1 \end{bmatrix} \begin{bmatrix} \cos\delta_2 & j\frac{\sin\delta_2}{N_2} \\ jN_2 \cdot \sin\delta_2 & \cos\delta_2 \end{bmatrix} \begin{bmatrix} \cos\delta_3 & j\frac{\sin\delta_3}{N_3} \\ jN_3 \cdot \sin\delta_3 & \cos\delta_3 \end{bmatrix} \begin{bmatrix} 1 \\ N_4 \end{bmatrix}$$

Where :

$$\delta_1 = \frac{2\pi}{\lambda} N_1 \cdot t_1 \qquad \text{.......... (12 a)}$$

$$\delta_2 = \frac{2\pi}{\lambda} N_2 \cdot t_2 \qquad \text{......... (12 b)}$$

$$\delta_3 = \frac{2\pi}{\lambda} N_3 \cdot t_3 \qquad \text{......... (12 c)}$$

If :

$A = N_o - N_4$, $B = \frac{N_2 N_4}{N_3} - \frac{N_o N_3}{N_2}$,

$$C = \frac{N_1 N_4}{N_3} - \frac{N_o N_3}{N_1} \quad , \quad D = \frac{N_1 N_4}{N_2} - \frac{N_o N_2}{N_1}$$

$$E = \frac{N_o N_4}{N_3} - N_3 \quad , \quad F = \frac{N_o N_4}{N_2} - N_2$$

$$G = \frac{N_o N_4}{N_1} - N_1 \quad , \quad H = \frac{N_1 N_3}{N_2} - \frac{N_o N_2 N_4}{N_1 N_3}$$

$$I = N_o + N_4 \quad , \quad J = \frac{N_2 N_4}{N_3} + \frac{N_o N_3}{N_2}$$

$$K = \frac{N_1 N_4}{N_3} + \frac{N_o N_3}{N_1} \quad , \quad L = \frac{N_1 N_4}{N_2} + \frac{N_o N_2}{N_1}$$

$$M = \frac{N_o N_4}{N_3} + N_3 \quad , \quad N = \frac{N_o N_4}{N_2} + N_2$$

$$O = \frac{N_o N_4}{N_1} + N_1 \quad , \quad P = \frac{N_1 N_3}{N_2} + \frac{N_o N_2 N_4}{N_1 N_3}$$

$$Q = \cos\delta_1 \cdot \cos\delta_2 \cdot \cos\delta_3 \quad ,$$
$$S = \cos\delta_1 \cdot \sin\delta_2 \cdot \sin\delta_3 \quad ,$$
$$T = \sin\delta_1 \cdot \cos\delta_2 \cdot \sin\delta_3 \quad ,$$
$$U = \sin\delta_1 \cdot \sin\delta_2 \cdot \cos\delta_3 \quad ,$$
$$V = \cos\delta_1 \cdot \cos\delta_2 \cdot \sin\delta_3 \quad ,$$
$$W = \cos\delta_1 \cdot \sin\delta_2 \cdot \cos\delta_3 \quad ,$$
$$Y = \sin\delta_1 \cdot \cos\delta_2 \cdot \cos\delta_3 \quad ,$$
$$Z = \sin\delta_1 \cdot \sin\delta_2 \cdot \sin\delta_3$$

$$a = \Big[(N_o - N_4) . \cos\delta_1 . \cos\delta_2 . \cos\delta_3$$

$$+ \left(\frac{N_2 N_4}{N_3} - \frac{N_o N_3}{N_2} \right) . \cos\delta_1 . \sin\delta_2 . \sin\delta_3$$

$$+ \left(\frac{N_1 N_4}{N_3} - \frac{N_o N_3}{N_1} \right) . \sin\delta_1 . \cos\delta_2 . \sin\delta_3$$

$$+ \left(\frac{N_1 N_4}{N_2} - \frac{N_o N_2}{N_1} \right) . \sin\delta_1 . \sin\delta_2 . \cos\delta_3 \Big]$$

$$+ j \Big[\left(\frac{N_o N_4}{N_3} - N_3 \right) . \cos\delta_1 . \cos\delta_2 . \sin\delta_3$$

$$+ \left(\frac{N_o N_4}{N_2} - N_2 \right) . \cos\delta_1 . \sin\delta_2 . \cos\delta_3$$

$$+ \left(\frac{N_o N_4}{N_1} - N_1 \right) . \sin\delta_1 . \cos\delta_2 . \cos\delta_3$$

$$+ \left(\frac{N_1 N_3}{N_2} - \frac{N_o N_2 N_4}{N_1 N_3} \right) . \sin\delta_1 . \sin\delta_2 . \sin\delta_3 \Big] \quad \ldots (13a)$$

and

$$b = \Big[(N_o + N_4) . \cos\delta_1 . \cos\delta_2 . \cos\delta_3$$

$$- \left(\frac{N_2 N_4}{N_3} + \frac{N_o N_3}{N_2} \right) . \cos\delta_1 . \sin\delta_2 . \sin\delta_3$$

$$- \left(\frac{N_1 N_4}{N_3} + \frac{N_o N_3}{N_1} \right) . \sin\delta_1 . \cos\delta_2 . \sin\delta_3$$

$$- \left(\frac{N_1 N_4}{N_2} + \frac{N_o N_2}{N_1} \right) . \sin\delta_1 . \sin\delta_2 . \cos\delta_3 \Big]$$

$$+ j \Big[\left(\frac{N_o N_4}{N_3} + N_3 \right) . \cos\delta_1 . \cos\delta_2 . \sin\delta_3$$

$$+ \left(\frac{N_o N_4}{N_2} + N_2 \right) . \cos\delta_1 . \sin\delta_2 . \cos\delta_3$$

$$+ \left(\frac{N_o N_4}{N_1} + N_1 \right) . \sin\delta_1 . \cos\delta_2 . \cos\delta_3$$

$$- \left(\frac{N_1 N_3}{N_2} + \frac{N_o N_2 N_4}{N_1 N_3} \right) . \sin\delta_1 . \sin\delta_2 . \sin\delta_3 \Big] \quad \ldots (13b)$$

So, the reflection loss for a triple-layer antireflection coating is

$$R = \frac{(A.Q + B.S + C.T + D.U)^2 + (E.V + F.W + G.Y + H.Z)^2}{(I.Q - J.S - K.T - L.U)^2 + (M.V + N.W + O.Y - P.Z)^2} \quad (14)$$

NUMERICAL APPLICATION AND RESULTS :

To illustrate the effect of cell surface coating with multi-layers, a Silicon solar cell is considered , and the reflection losses is computed for different materials usually used for layers surface coating .

Figs. (1,2,3,4 and 5) shows the reflection losses against wave-length for the silicon solar cell coated by a single-layer made of MgF_2 or SiO_2 or Al_2O_3 or SiO or CeO_2.

Fig s. (6,7 and 8) illustrate the reflection loss as function of wave-length for the different layer materials used and with different layer thickness .

Fig s. (9 and 10) show the reflection losses in case of triple layer antireflection coatings.

Table (1) gives the minimum values for antireflection losses with the multi-layer antireflection coating. Also , Fig. (11) illustrates the comparison between these cases.

CONLUSION :

To improve the solar cell conversion efficiency the reflection loss may be reduced by the use of multi-layer antireflection coatings . From the above analysis and applications, the effects of multi-layer antireflection coatings for silicon solar cell can be summerized as :

1 - Coating the cell with SiO_2 as single - layer, the reflection loss is reduced from 31 % to 18.2 % .

2 - Coating the cell with MgF_2 - TiO_2 as double - layer, the reflection loss will be 5.3 % .

3 - Coating the cell with MgF_2- $ZrSiO_4$ - TiO_2 , as triple - layer, the reflection loss is 2. 4 % .

So, for increasing the cell conversion efficiency and regarding economical considerations, it is recommended to use MgF_2 - $ZrSiO_4$ - TiO_2 as triple - layer antireflection caoting to reduce the refleation loss from 31 % to 2.4 % .

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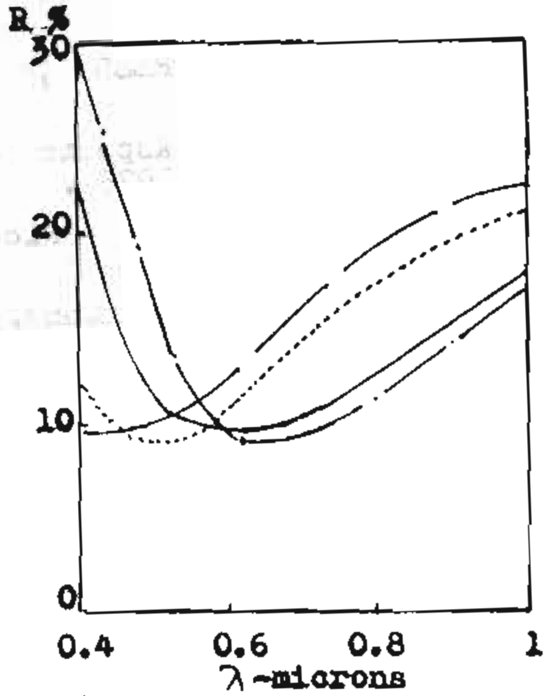

Fig (1): MgF_2/Si-Si

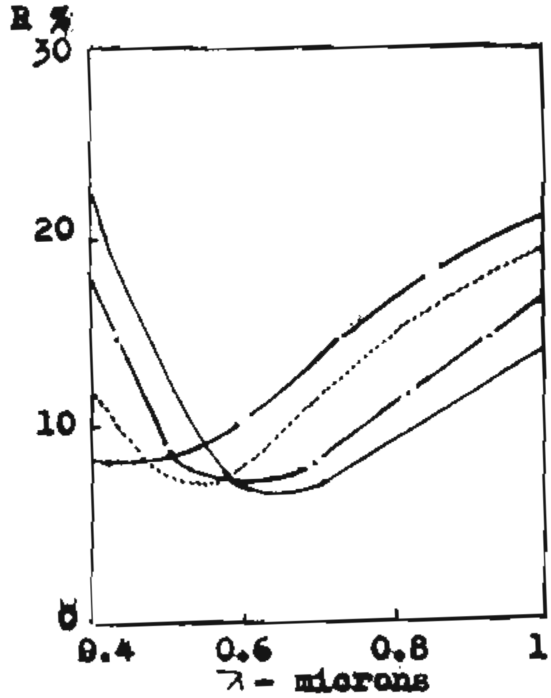

Fig (2): SiO_2/Si-Si

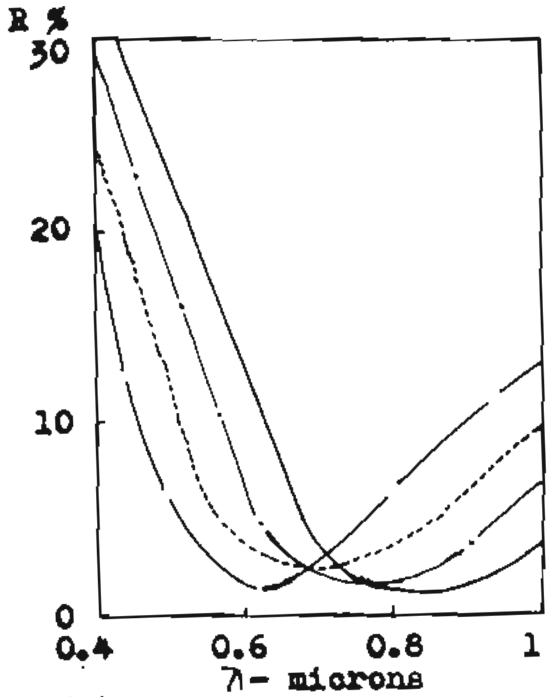

Fig (3): Al_2O_3/Si-Si

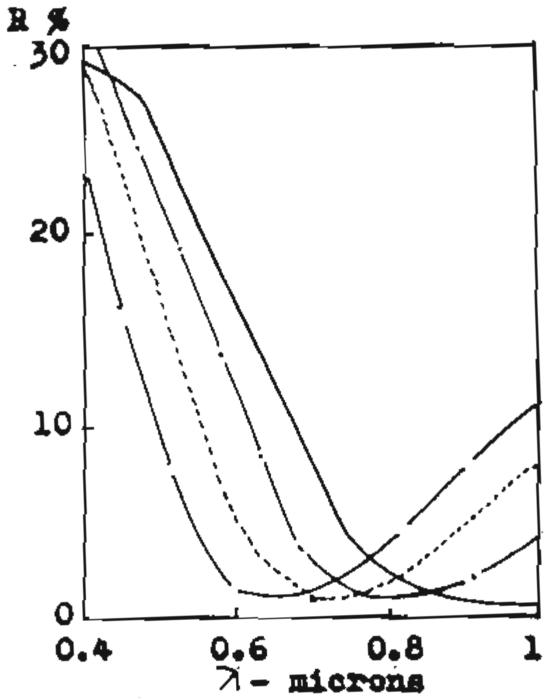

Fig (4): SiO / Si-Si

— — — t_1 = 0.08 microns ··········· t_1 = 0.09

—·—·— t_1 = 0.10 ———— t_1 = 0.11

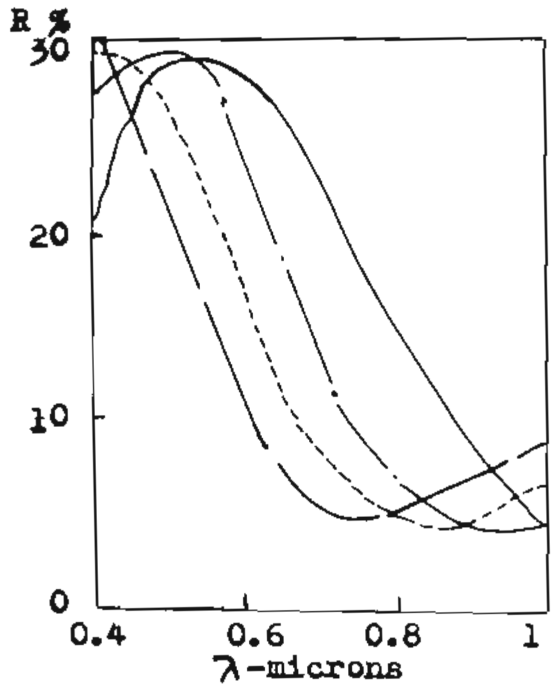

Fig (5): CeO_2 / Si-Si

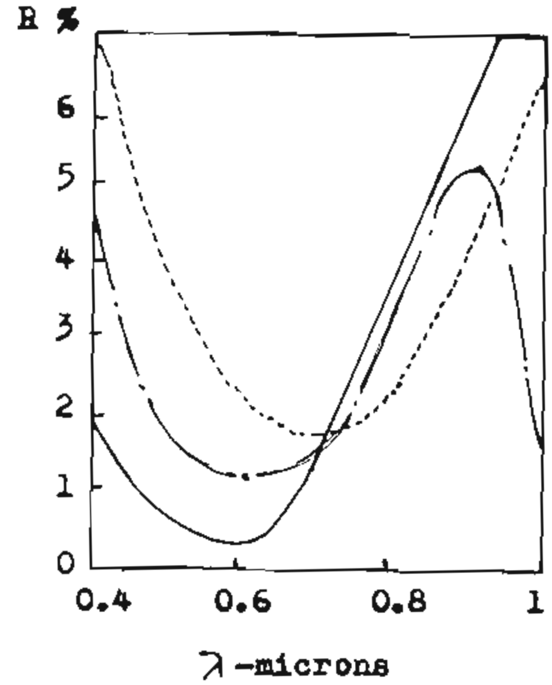

Fig (6): MgF_2-TiO_2 / Si-Si

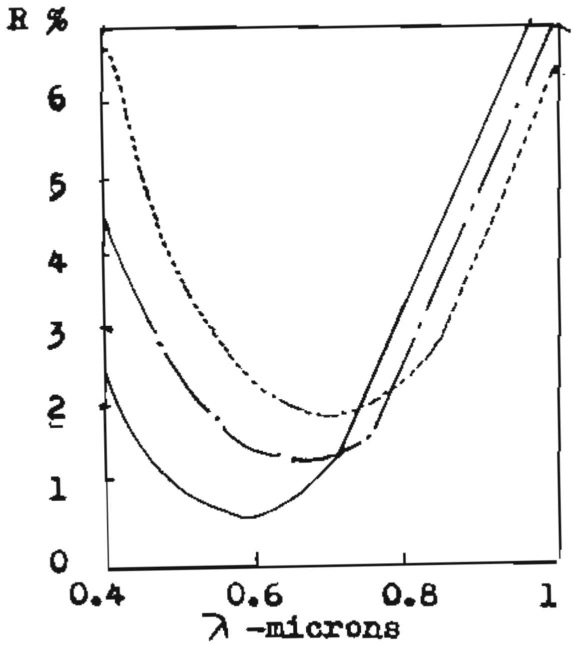

Fig (7): LiF-TiO_2 / Si-Si

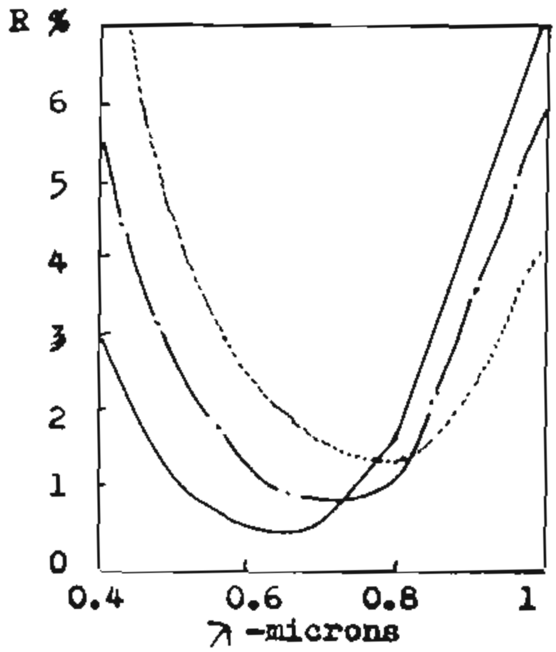

Fig (8): SiO_2-TiO_2 / Si-Si

Fig (5) : —— —— t_1 = 0.08 ——······ t_1 = 0.09

—— - —— t_1 = 0.10 ———— t_1 = 0.11

Figs (6,7,8) ———— t_1 = 0.10 —— - —— t_1 = 0.11

- - - - - - - - - t_1 = 0.12

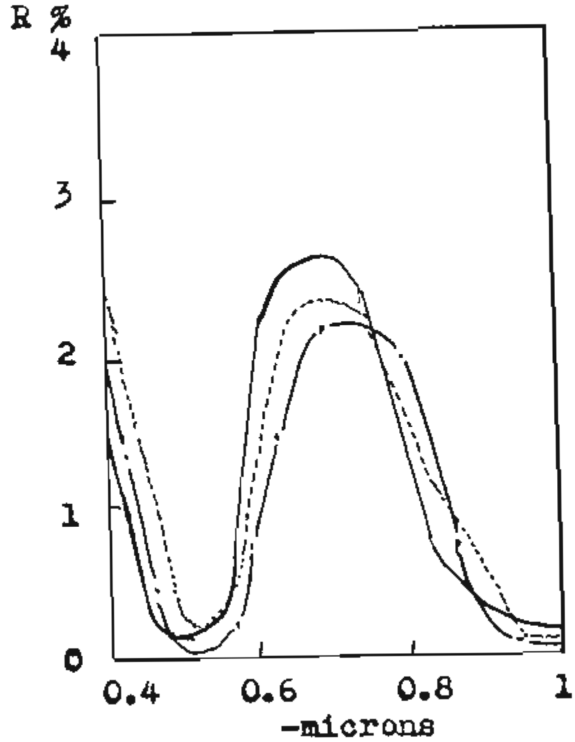

Fig (9): MgF_2 - Zr SiO_4 - TiO_2 / Si - Si

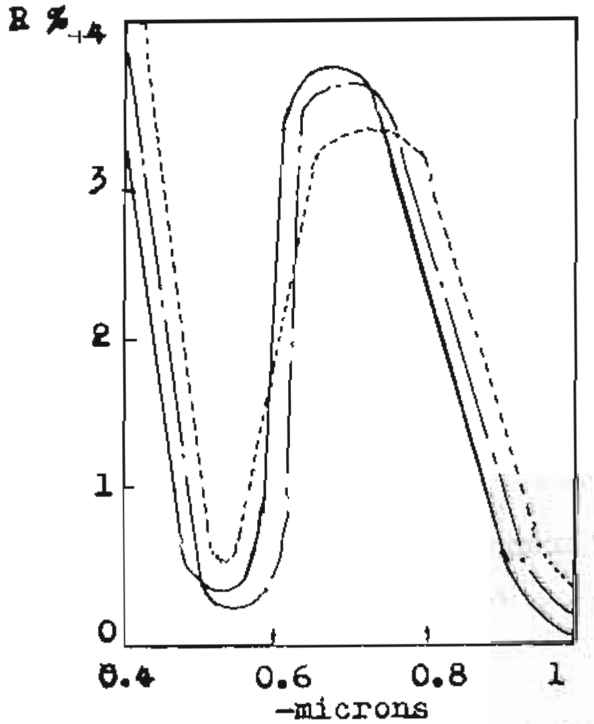

Fig (10): SiO_2 - Zr SiO_4 - TiO_2 / Si - Si

———— t_1 = 0.85   —— · —— t_1 = 0.90

.... t_1 = 0.95

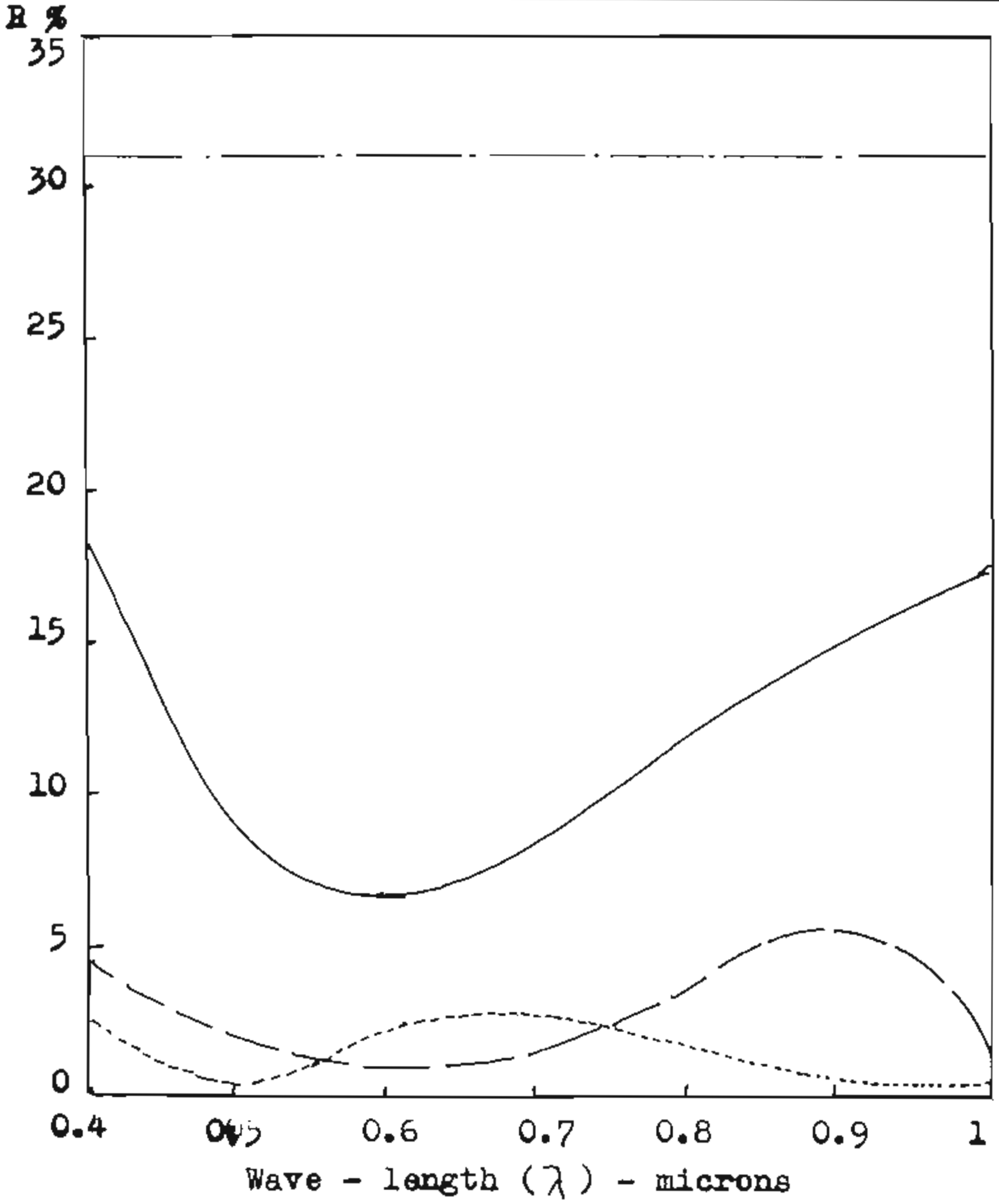

Fig (11): The reflection loss as a function of the wave - length for a different cases of antirefledtion coatings .

—·—·— Uncoated

———— Single - layer (SiO_2)

— — — — Double - layer (MgF_2-)TiO_2)

.... Triple - layer (MgF_2- $ZrSiO_4$ - TiO_2)

Table (1) : The reflection loss values for multi-layer antireflection coating on silicon solar cell .

anti-relfection coatings	Materials			Layer thickness (microns)			reflection loss %
	first layer	second layer	third layer	first layer	second layer	third layer	
uncoated	-	-	-	-	-	-	31
single-layer	SiO_2	-	-	0.10	-	-	18.2
double-layer	MgF_2	TiO_2	-	0.11	0.045	-	5.3
triple-layer	MgF_2	$ZrSiO_4$	TiO_2	0.09	0.066	0.048	2.4