EFFECTIVENESS OF SURFACE TEXTURING AND OPTICAL WIDTH IN MINIMIZING THE OPTICAL LOSS OF A SOLAR CELL: A SIMULATED STUDY

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Abstract: Optical loss is one of the prime factors of a solar cell. If the parameters responsible for the optical loss are not dealt with properly, the efficiency of the solar cell is hampered significantly. Anti-Relfelction coating is a commonly studied mechanism to reduce optical loss. This research paper presents a simulated study on the reduction of optical loss by employing surface texturing and enhancing the optical path inside the active layer of a given solar cell. The surface textures have been employed on both the front and rear surfaces of the solar cell. Also, for the analysis purpose the various types of structure have been considered. The analysis shows that, among considered types, Upright Hillocks shows the minimum reflection. Further, the effectiveness of a particular surface structure is found to be depend on the characteristic angle. Similarly, the total optical path travelled through the active layer is found to be increase with increase in the propagation angle of the ray inside the active layer of the solar cell.

Keywords: optical loss; surface texturing; ray tracing; optical width

1. Introduction:

In the present time, solar cells are almost used everywhere, starting from very remote areas to metropolitan cities. In designing the structure of a solar cell in a research environment, the parameters are chosen in such a way that the maximum efficiency is the main consideration rather than the price. The theoretical efficiency of a solar cell is about 86.8% [1], whereas in practical fields it is approximately 29%. This difference is mainly due to the assumption that each photon is absorbed by the electrons, which in turn take part in the conduction of electricity without undergoing any recombination or any other losses which is never possible in a working environment. So in this study, focus has been given on maximizing the efficiency of a solar cell under the standard spectrum AM1.5. For the above purpose, different simulators have been used, which are discussed in the later sections. Optical losses contribute a major part in the downfall of efficiency. It can be reflection, absorption in the unwanted layer and recombination or transmission [2]. So, in the present study, the main focus is on optical loss of solar cells. The optical losses of a solar cell can be managed by applying the following ways.

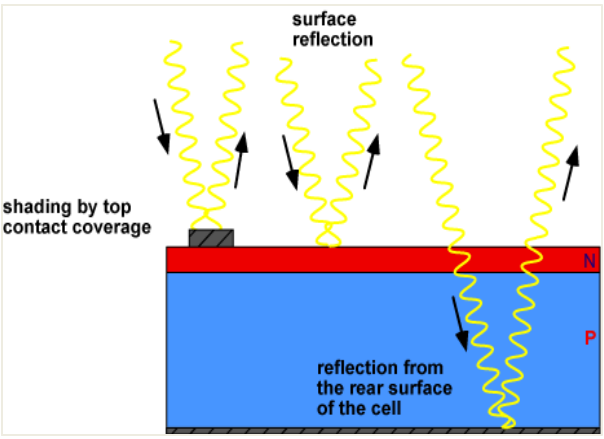


Figure 1:- Optical loss in a solar cell [4]

Minimizing the top contact coverage, using anti reflection coatings (ARC)[3], by using surface texturing, increasing absorption within the silicon by thickening the material, increasing the optical path length by light trapping ability and also by surface texturing.

The thickness of a ARC is chosen in such a way that the wavelength in the dielectric material is 1/4th of the wavelength of the incoming wave. It can be given as-

$D1=\lambda 0/4n1$

Where n1 is the R.I of the anti reflection coating and λ0 is the wavelength of the incident light in free space. However, nowadays, double-layer anti-reflection coatings are being used. It can be more precisely understood in the following figures 2 and figure 3.

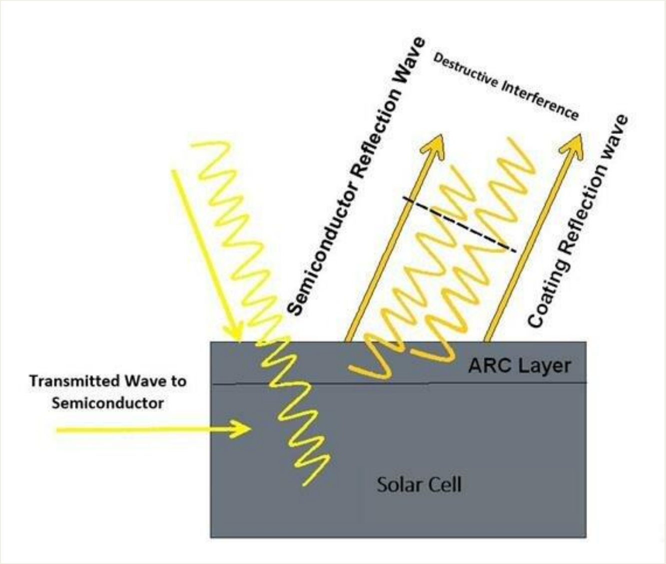


Figure 2 Anti-reflection coating [5]

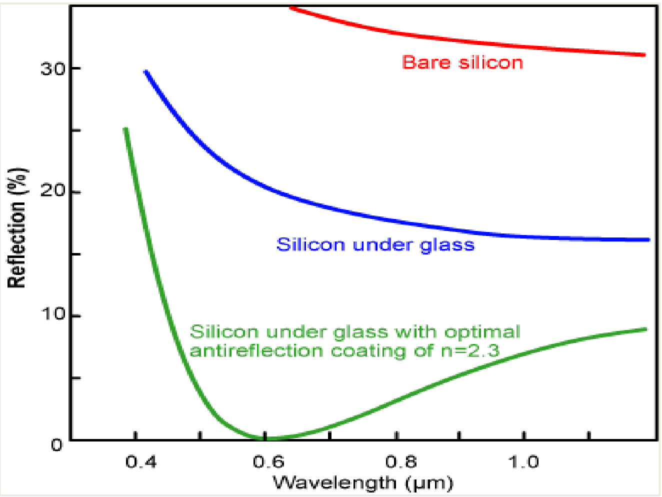


Figure 3: Comparison of the surface reflection with and without anti reflection coating [4]

Surface Texturing

In this study, different surface structures have been considered to minimize the reflection. It can be achieved by etching along the faces of a crystal plane. The resultant flat surface of the c-Si is being converted into pyramids. One such example of a pyramid is shown in figure 5. The pyramids is called Random Pyramid where the surface of the c-Si is appropriately aligned with respect to its internal atoms. Another type of surface texturing is Inverted Pyramids where the pyramids are etched down into the silicon surface rather than pointing upwards as mentioned in athe above case. A photograph of such inverted pyramids is shown in figure 6.

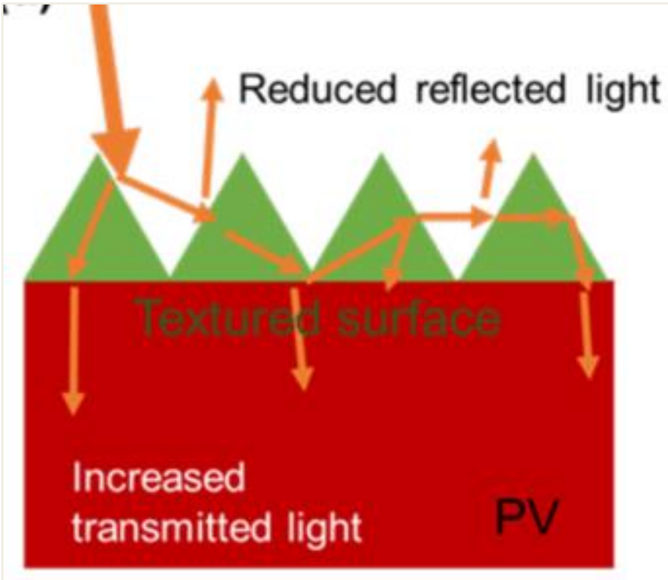


Figure 4:- Surface Texturing [6]

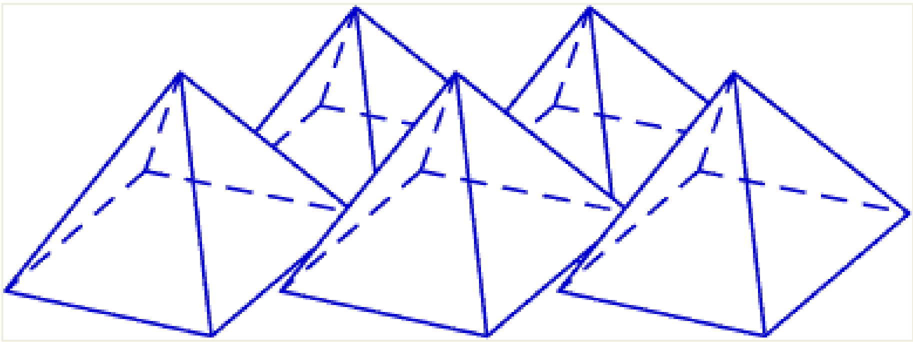


Figure 5: A square-based pyramid [4]

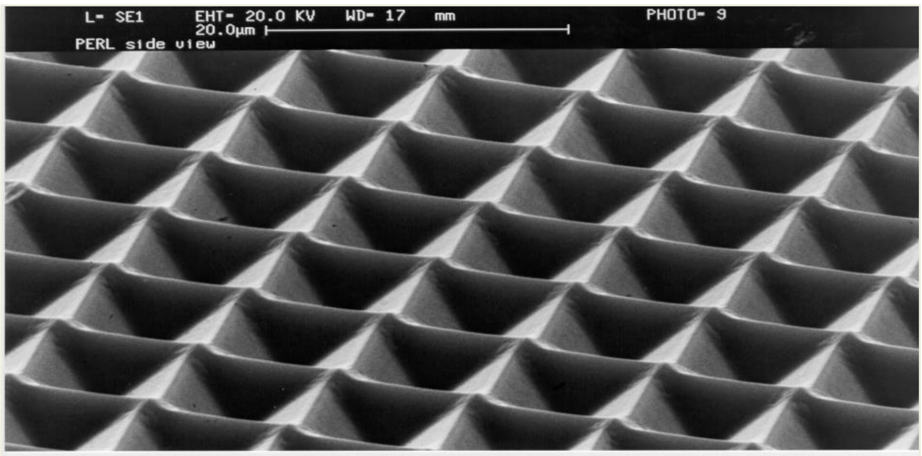


Figure 6: Inverted pyramids [4]

In the present research, the reflection has been minimised by considering different types of surface texturing, for example- V Grooves, Inverted pyramids etc, which are elaborately discussed in Research Methodology and therefore calculate the minimum losses in terms of current densities.

Material Thickness

The present study also focuses on the trapping of light in a solar cell to increase the efficiency. For the above purpose, either the width of the c-Si needs to be increased or needs to increase the path length of the light. But in reality, a very heavy solar cell is not very convenient to use. Therefore, thin films are usually designed with a reflector on the rear side so that light makes multiple passes and absorption is increased. Light trapping increases the optical path length. Optical path length generally refers to the distance than un-absorbed photons may travel within the device before it escapes out. In the case of silicon with R.I 3.5 the optical path length increases by ~50. Light trapping is usually achieved by changing the angle at which light is incident on the silicon surface. Therefore, light on a textured front and rear surface can increase the optical path for more understanding some images are shown in figure 7.

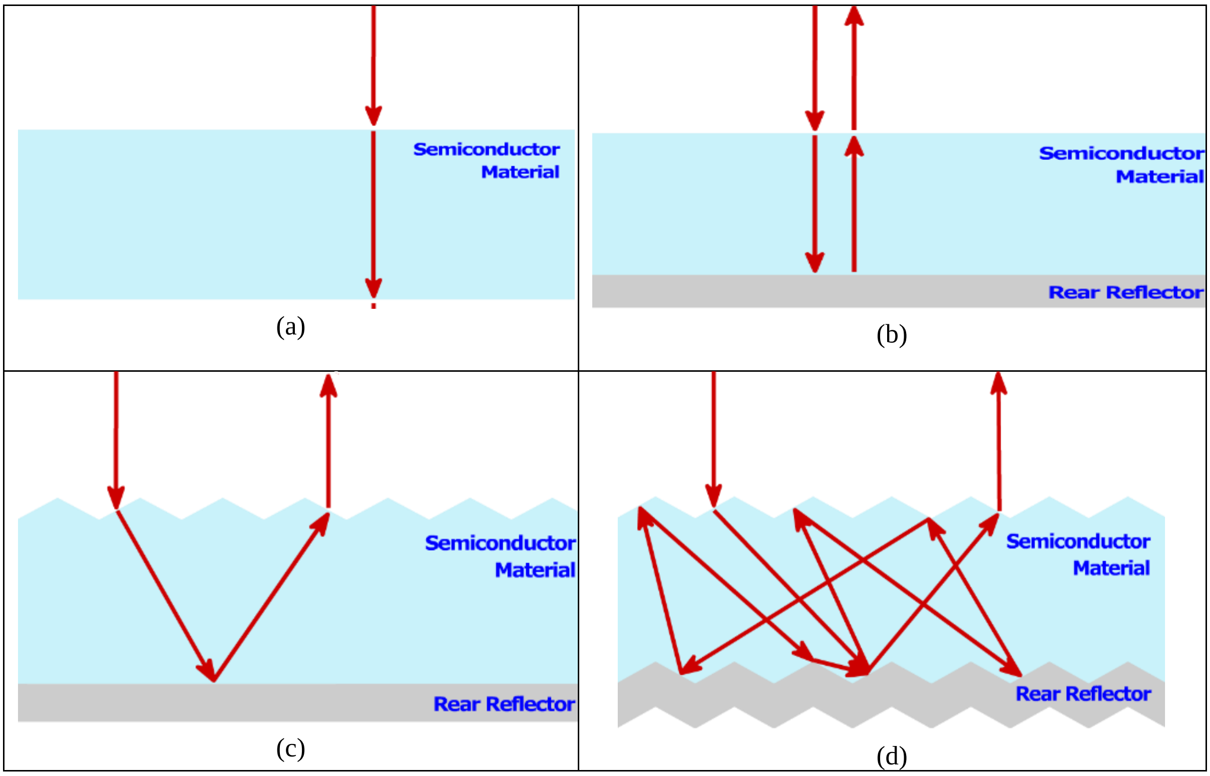


Figure 7: Rear surface reflection (a)Without rear reflector, (b)With rear reflector, (c)Rear reflector with surface texturing, (d)Rear and front texturing [4]

Optical losses, surface texturing, ray tracing, optical path length enhancement in a solar cell are some of the many important topics of solar cell design. Many researchers have been able to calculate these losses using a specific simulator called OPAL 2 [7]. In reference [8], the light trapping performance been considered over a range of 300-1200nm using the standard spectrum AM1.5. ARC is one of the popular methods to reduce optical loss by reflection. Any ARC like silicon nitride (SiNx) is chosen in such a way so that recombination is less and absorption is more [9].

2. Methodology

In the present study, analysis has been carried out for reflection, absorption of the front surface and back surface of a photovoltaic solar cell using OPAL2 and Wafer Ray Tracer simulators. The analysis of optical path length enhancement and optical width has been carried out using the path-length simulator, Detail working of the above simulators and the applied equations are explained below.

OPAL2 is an optical simulator used to calculate different parameters of a solar cell such as reflection from the front surface, the absorption in the thin film coatings, and the transmission into its substrate for a given structure.

The above stated parameters are calculated in terms of current densities as shown in Table 1 having wavelengths ranging from 300 to 1300 nm. The structure of the solar cell is provided by the user. Therefore, we can calculate the fraction of losses for a particular incident wavelength and can determine the quality of the given structure.

The wafer Ray Tracer determines the photo generated current density in a solar cell or test structure under a selected spectrum. While the OPAL 2 accurately calculates reflection, transmission and thin film absorption on a single surface, this particular simulator also includes the effect of the considered wafer and both the surfaces. Therefore, in this case, the structure of both the surfaces are considered i.e for the front and rear surface. It permits the evaluation of all the optical losses and light trapping from the surfaces and gives an approximate idea of the efficiency of the selected surfaces. The calculated photo generated current in a wafer can be extracted from a solar cell made from the wafer.

The purpose of any solar cell is to convert photon energy into electrical energy. Now, in that case, the efficiency of a solar cell is more if the light is neither transmitted nor reflected back to the surroundings, rather it is absorbed by the atoms to eject the electrons. It will be possible only if light is trapped inside the active layer for a longer period of time.

The trapping of light can be enhanced in two ways, propagating the light obliquely inside the solar cell and reflecting the light inside from and back layers of the active medium of the cell.

In the present study, the second option has been analysed to increase the light trapped in the solar cell. Also, the optical path length has been studied for different widths of the cell.

The optical path length enhancement is given as-

Z=Wopt/W

where, W is the actual width of the active layer & Wopt is the total path travelled by light within the active layer (Optical width)

From the above equation shows that when Wopt is more, Z is automatically more, which is beneficial for our research. A schematic diagram for better understanding is shown in figure 8.

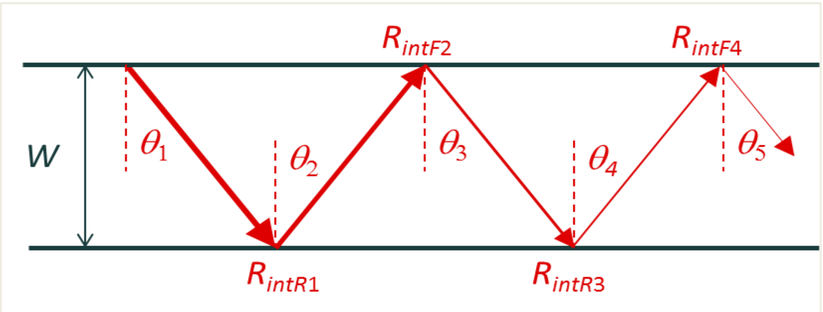


Figure 8: Internal reflection [10]

2.1. Major Input parameters and their related values (if any)

- Standard spectrum: AM1.5,
- The surface texturing is done in a regular fashion,
- The Zenith angle is kept at 0º or 45º as per the requirements of calculation and the material properties are fixed.
- Surface texture morphology such as-a) Upright Pyramids b) upright Hillocks c) Inverted Pyramids d)V grooves are considered
- A substrate material such as silicon or glass.
- An ARC material such as Sio2 SiNx,
- A superstate material such as air, silicon.
- characteristics angle of the surface texture, such as 45º, 50º, 55º and 60º are considered.

- Thickness ranging from 180-500 is taken

2.2. Formulae used to calculate the reflection and transmission coefficients

For internal reflection, Snell's law is followed

$$n1\sin\theta1= n2\sin\theta2 \qquad (1)$$

where, θ1 and θ2 are the angle at which light is incident at the interface and, n1 and n2 are refractive indices at the interface. By rearranging Snell's law we have,-

$$\Theta2=\sin^{-1}(n2/n1\sin\theta1) \quad (2)$$

And, when light passes from a high RI index to a low RI, there is a possibility of total internal reflection where θ2 is considered to be zero.

Therefore,

$$\theta1= \sin^{-1}(\frac{n1}{n}) \qquad (3)$$

Now the amount reflected is given by Fresnel law-

$$Rll = \tan2\ (\theta1-\theta2)/\tan\ (\theta1+\theta2)\ \text{(parallel to the surfaced)} \qquad (4)$$

$$R\perp= \sin2\ (\theta1-\theta2)/\sin\ (\theta1+\theta2)\ \text{(perpendicular to surface)} \qquad (5)$$

The average is which the proportion of light reflected is-

$$R= (Rll + R\perp)/2 \qquad (6)$$

and the proportion of light transmitted is given by-

$$T= 1-R \qquad (7)$$

2.3. Formulae used to calculate the optical width (Wopt) and optical path length enhancement (Z)

$$Z= Wopt/W \qquad (8)$$

But,

$$Wopt= \sum_{p=1}^{\infty} f\text{lpdp} \qquad (10)$$

where, fLp is the fraction of the ray intensity that is lost (i.e., not reflected) at the end of pass p, and dp is the distance the light has travelled after pass p; this distance depends on the sample width W and the angle of propagation θ (defined by the users) by the expression.

Again,

$$dp= \sum_{q=1}^{p} W\cos\theta\text{q} \qquad (11)$$

The fraction of the ray intensity that is lost at the end of pa

$$fLp = fp \cdot (1 – Rp), \qquad (12)$$

where Rp is the internal reflection at the end of pass p, and fp is the fraction of the ray intensity remaining just prior to that reflection, given by

$$fp = 1 \text{ for } p = 1, \text{ and} \qquad (13)$$

$$fp = fp–1 \cdot(Rp–1), \text{ for } p > 1. \quad (14)$$

Finally, the fractions lost through the front and rear surfaces are given by-

$$fF=\sum_{p=2,4,6,\ldots}^{\infty} f\text{Lp} \qquad (15)$$

$$fR=\sum_{p=1,3,5\ldots,\ldots}^{\infty} f\text{Lp} \qquad (16)$$

Hence, putting the value of (15) and (16) in (10) and (12) the value of Wopt is calculated. Then, by putting the value of Wopt in equation (8) Z is calculated.

3. Results and Discussions

The results of various parameters such as optical losses, surface texturing, and optical path length enhancement are incorporated in this section. The findings have been listed and discussed in the following divisions.

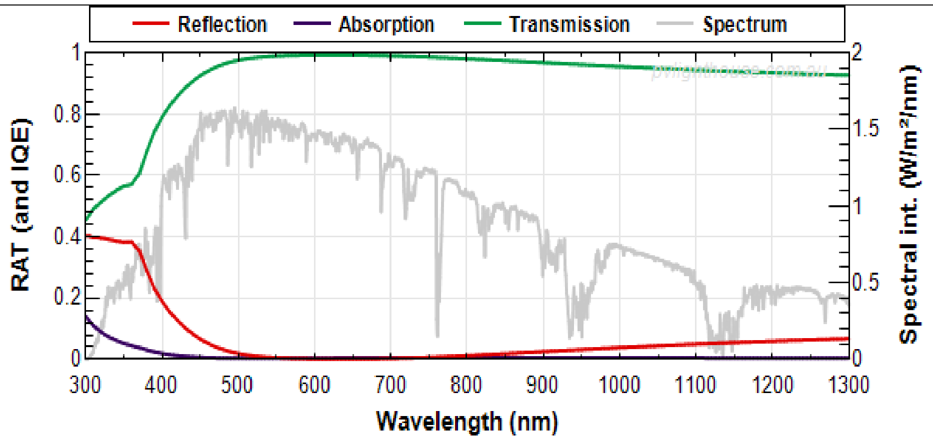
A. Optical loss with different structures on the front surface: Using OPAL 2

I. Optical loss with V groove structure

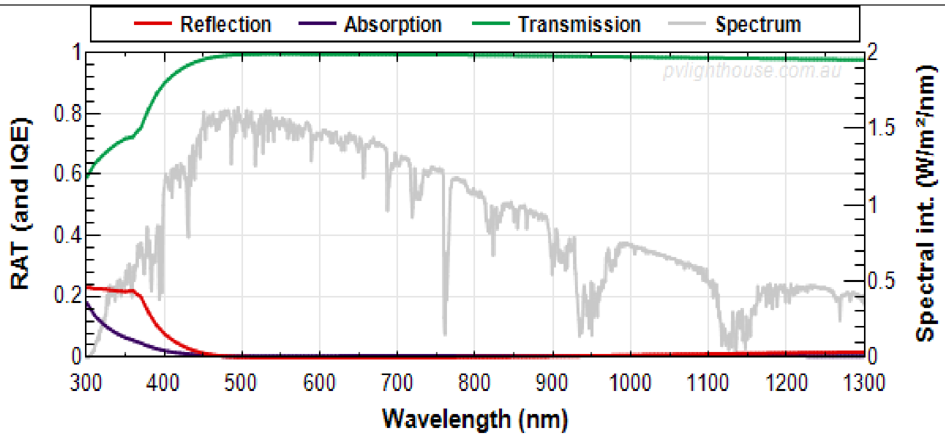
Table 1: Calculation of the photo current density for V grooves surface texturing at different characteristic angles

Sl. No.	Parameters	Characteristic angle in degree			
		45	50	55	60
1	Incident(Jinc)	44	44	44	44
2	Reflected(Jr)	1.15(3.3%)	1.10	1.08	0.44
3	Absorbed in Films(Ja)	0.31(.7%)	0.31	0.31	0.33
4	Absorbed in Substrate(Jg)	42.54(96%)	42.59	42.61	43.23

The graphical representation of reflection, absorption and transmission for the V groove surface texturing with a characteristic angle of 45º and 50º is shown in Figure 9(a) and (b). The figures also contain the standard spectrum used to test the solar cell.



(a)



(b)

Figure 9: The Reflection, Absorption and Transmission values for V grooves for characteristic angles of 45º and 60º corresponding to wavelengths 300-1300

From the above graph, the approximate average values of Refection, Absorption and Transmissions are found to be 0.0510, 0.0046, 0.9328 0.0204, 0.0049, 0.9443 respectively for the characteristic angle of 45º. The corresponding values for 60º are 0.0204, 0.0049, 0.9443.

From the above results of the reflection, absorption & transmission co-efficient and their corresponding current densities as shown in table 1,2,3,4 respectively, we can conclude that as the groove angle increases, the transmission also increases, which is the most suitable condition for a Solar Cell to be used. Therefore, V grooves with a characteristic angle of 60º can be used.

II. Optical loss with Upright Pyramids structure

Findings with this surface texturing are presented in
Table 2. The changes of important parameters with the given surface texturing for the characteristic angles of 45º and 60º are shown in Figure 10. From the graph, the approximate average values of Refection, Absorption and Transmissions are found to be 0.5334, 0.0046, 0.9292 respectively for the characteristic angle of 45º. The corresponding values for 60º are 0.0334, 0.0049, 0.9386.

Table 2: Calculation of the photo current density for Upright Pyramids surface texturing at different characteristic angles

Sl. No.	Parameters	Characteristic angle			
		45	50	55	60
1	Incident(Jinc)	44	44	44	44
2	Reflected(Jr)	1.15 (2.6%)	1.02	0.93	0.72
3	Absorbed in Films(Ja)	0.31 (0.7%)	0.32	0.32	0.33
4	Absorbed in Substrate(Jg)	42.54 (96.7%)	42.67	42.76	42.95

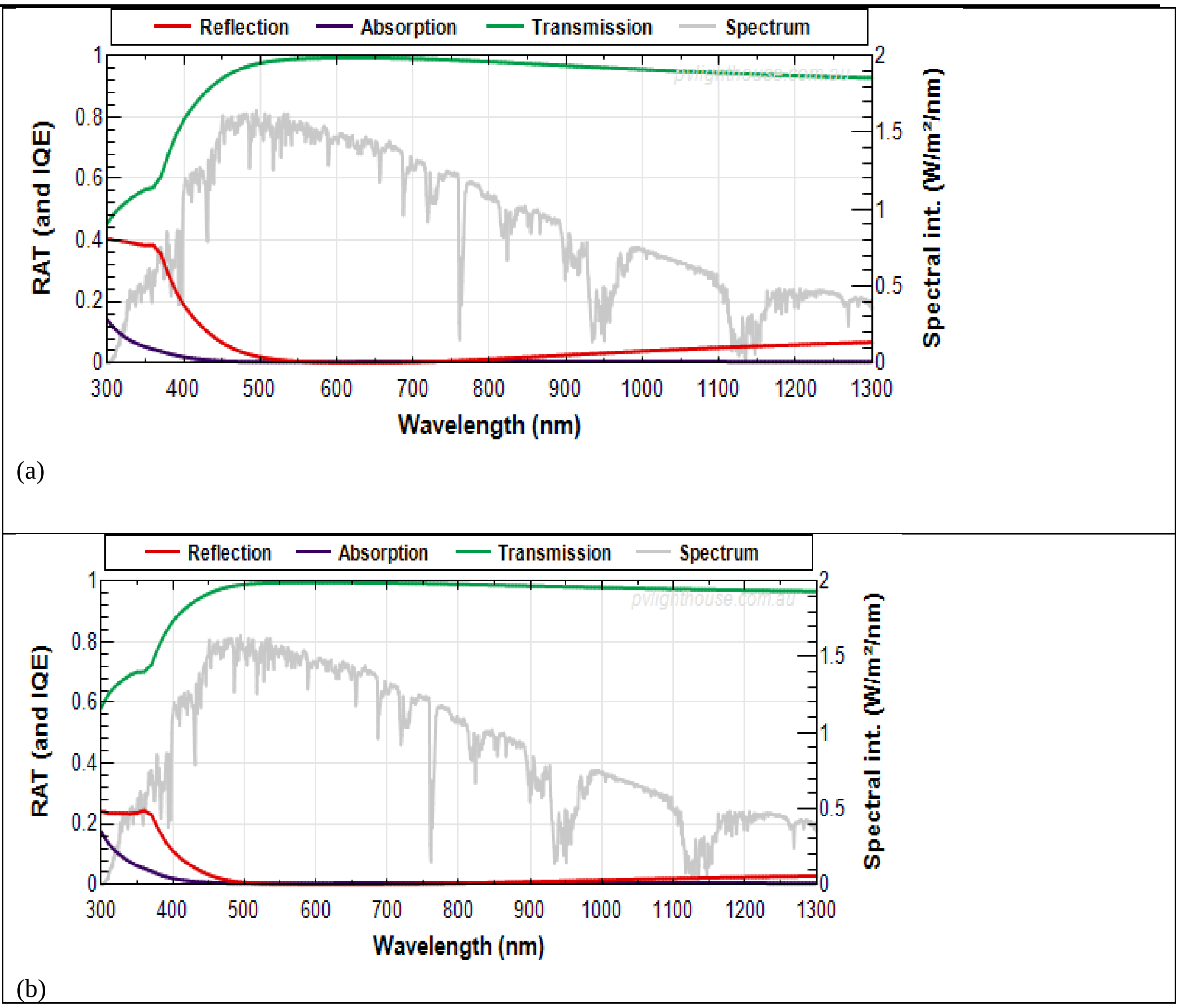


Figure 10: The Reflection, Absorption and Transmission values for Upright Pyramids with characteristic angles of 45º and 60ºcorresponding to wavelengths of 300-1300 nm

From the above results of the reflection, absorption & transmission co-efficient and their corresponding current densities, it can be concluded that as the characteristic angle increases, the transmission also increases, which is the most suitable condition for a SOLAR Cell to be used. Therefore, Upright Pyramids with a characteristic angle of 60 can be used.

III. Optical loss with Upright Hillocks structure

Table 3: Calculation of the photo current density for Upright Hillocks surface texturing at different characteristic angles

Sl. No.	Parameters	Characteristic angle			
		45º	50º	55º	60º
1	Incident(Jinc)	44	44	44	44
2	Reflected(Jr)	1.50(3.4%)	1.39	1.32	1.11
3	Absorbed in Films(Ja)	0.31(0.7%)	0.31	0.31	0.32
4	Absorbed in Substrate(Jg)	42.19 (95.9%)	42.30	42.36	42.57

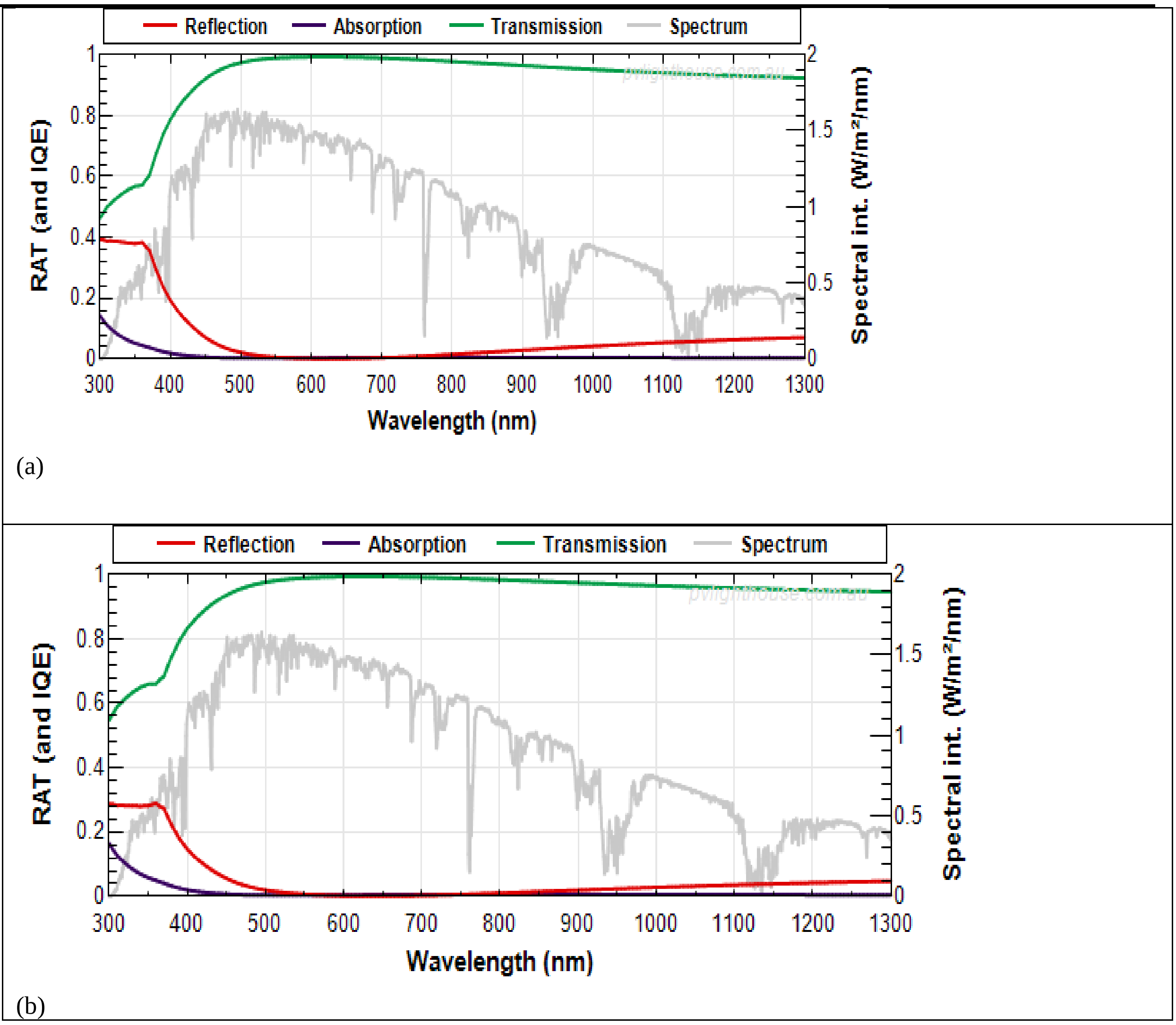


Figure 11: The Reflection, Absorption and Transmission values for Upright Hillocks with characteristic angles of 45º and 60ºcorresponding to wavelengths of 300-1300nm

From the graph, the approximate average values of Refection, Absorption and Transmissions are found to be 0.0708, 0.0046, 0.9215 respectively for the characteristic angle of 45º. The corresponding values for 60º are 0.0524, 0.0047, 0.9298.

From the above results of the reflection, absorption & transmission co-efficient and their corresponding current densities, it can be concluded that as the characteristic angle increases, the transmission increases, which is the most suitable condition for a solar ce to be used. Further, among the different surface structures, the Upright Hillocks shows the most favourable condition. Therefore, Upright Hillocks with a characteristic angle of 60 can be used.

B. Optical loss with different structures on the front and back surfaces: Calculated using Wafer Ray Tracer

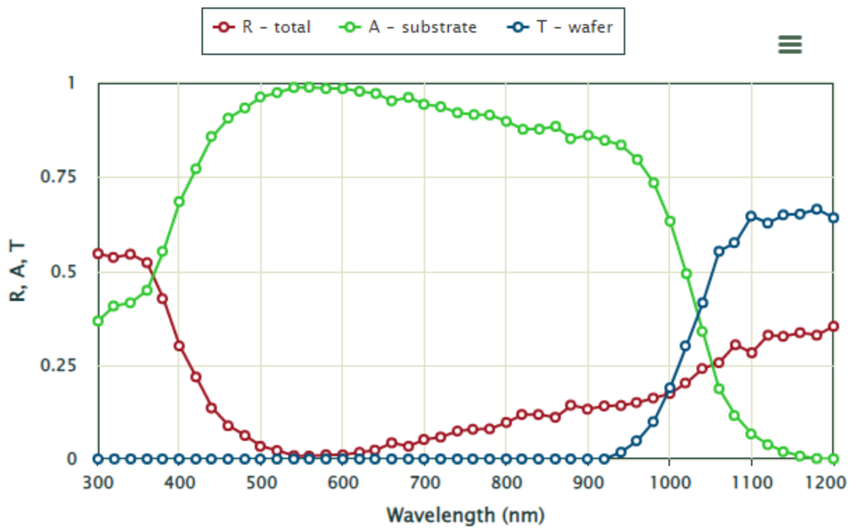
In this case, standard spectrum (AM I.5g) is considered with Zenith-45, Azimuth-0. The considered wavelength range is from 300 to 1200 nm respectively and wavelength interval is taken as 30 nm. The results have been analyzed for the following five cases.

I. Front surface: plain, rear surface:plain
II. Front surface: Upright pyramids with periodicity regular, rear surface:plain
III. Front surface: Inverted Pyramids with periodicity regular, rear surface:plain
IV. Front surface: X Grooves with periodicity regular, rear surface:plain
V. Front surface: Y Grooves with periodicity regular, rear surface:plain

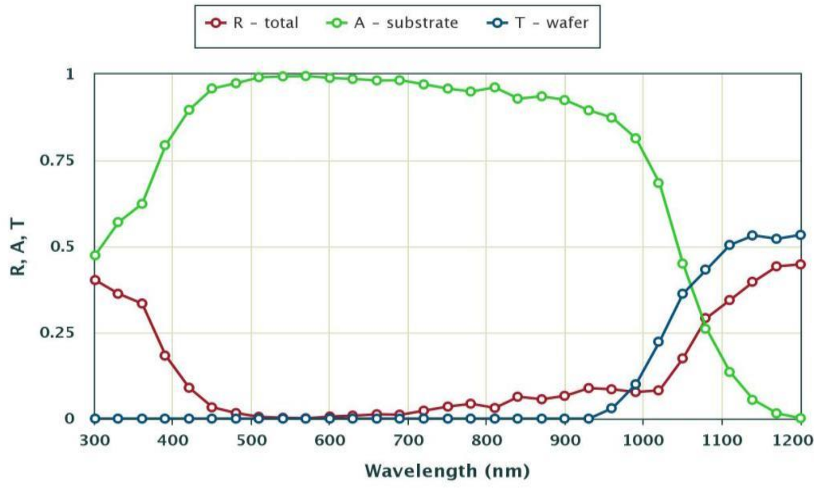
In all the cases, the incident current density was (Jinc) 32.73 ± 6.509e-15 (mA/cm2). The optical findings for the above cases are listed in Table 4. Two representative graphs of the optical parameters are also shown in Figure 11 (a) and (b). These two figures are for case- I and case-v. From the figures and the table, it was found that if x groove structure is considered, then the optical loss from the front and rear surface becomes less compared to others.

Table 4: Calculation of lost current densities

Optical Parameters	Fraction of Jinc (%)				
	Case-I	Case-II	Case-III	Case-IV	Case-V
Reflected-external (JR,ext)	13.09	3.315	4.953	1.163	5.004
Reflected-escape (JR,esc)	1.735	4.579	2.983	5.690	3.184
Transmitted	9.240	3.084	5.858	3.210	7.563
Absorbed- front films (JA,F)	0.5841	1.031	1.053	1.055	0.8539
Absorbed- rear films (JA,R)	6.192e-16	2.434e-15	2.004e-15	2.095e-15	8.122e-16
Photo generation (abs) JG	75.32	87.87	85.03	88.80	83.31



(a)



(b)

Figure 12: The Reflection, Absorption and Transmission characteristics and wavelength for case-I and case-V

C. Optical width and optical path length enhancement

The optical width and optical path length enhancement were studied for the width of 200**µm, 300µm, 400µm and 500µm.** In this case, the internal reflection coefficients from the front (RintF) and rear (RintR) surface were taken as 0.9. The angle of propagation (θ) of the light in the material between the front and rear surfaces was taken from 40º to 90º from the 1st, 2nd, and 3rd passes. On the other hand, the angle of propagation (θ) for all other subsequent passes was considered as 60º. More detail is given in Table 5.

Table 5: Angle of propagation of the ray in different passes through the medium

Observation number	Angle of propagation (θ) in deg.			
	Pass-1	Pass-2	Pass-3	All other passes
1	40	40	40	60
2	50	50	50	60
3	60	60	60	60
4	70	70	70	60
5	80	80	80	60
6	90	90	90	60

Table 6: Values of Z and (Wop) for different angles of propagation and active layer widths

Observation number	Propagation angles (Deg)	Z values	Wop values for different width of active layer (**µm)**			
			200	300	400	500
1	40	18.12	3623.1	5434.6	7246.2	9057.7
2	50	18.79	3758.8	5638.1	7517.5	9396.9
3	60	20	3999.6	5999.3	7999.1	9998.9
4	70	22.50	4500.3	6750.4	9000.5	11250.6
5	80	30.18	6036.8	9055.2	12073.6	15092
6	90	-------	---------	--------	---------	---------

The values of the optical width (total path travelled by the ray) (Wop) in the active layer and the optical path length enhancement (Z) were calculated separately for all the considered angles (total of 6 observations in ref to Table 5). They were also calculated for all the considered widths of the active layers. In the observation, the optical width was found to be increase with increase in both angle of propagation as well as with the increase in width of the active layer. On the other hand, the value of Z was found to increase with the increase in angle of propagation. However, the value of Z remains the same across the width of the active layer. Both Z and (Wop) become undetermined for the propagation angle of 90°. A summer of all the values of Z and (Wop) are given in Table 6.

4. Conclusions

The presence study shows that to reduce the optical losses, surface texturing of both front and rear surface is important along with anti reflection coating and a suitable light trapping model. The above parameters not only reduce the optical losses but also increase the optical width, which in turn increases the absorption of radiation in a solar cell. This provides more radiation to be converted into electrical energy.

The present research shows that for the front surface V-grooves with a characteristic angle of 60° can be used for better performance. This gives maximum transmission from the front surface. Also, another best structure to reduce the reflection is found to be X groove with a characteristic angle of 60°.

The optical width and optical path length enhancement are increased when the thickness of the solar cell is increased. However, just to increase the optical path length, it is not recommended to increase the thickness of a solar cell, as it will make the cell a bulky one. The way to increase the optical path length is by controlling the angle of propagation. In the present study, the optical path length was found to be the maximum for angle of propagation of 80°across all the thickness of the active layer considered in the study. Therefore, while manufacturing a solar cell, the above points can be taken into consideration.

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