ANALYSIS OF SILICON DIOXIDE AND SILICON NITRIDE ANTI REFLECTION COATING FOR SILICON SOLAR CELL

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ABSTRACT

In this research, the analysis of silicon dioxide and silicon nitride for single and double layer thin film coatings on the reflectance spectrum of silicon surfaces has been investigate. The research has been carried out using ATLAS device simulator by Silvaco. This research is focusing to obtained higher efficiency and lower reflectance by different wavelength, thickness and refractive index. The material used for AR coating also important to give the lowest reflection in improving the efficiency. The ratio of available photocurrent is often known as external quantum efficiency. The source photocurrent is the amount of current generated by the light source and the available photocurrent is the amount of the current absorbed by semiconductor. By comparing the plot of spectrum response and the reflectance of analysis with and without AR coating, solar cell with ARC is more efficient. With this analysis it was concluded that the effect of the wavelength, refractive index and the thickness of the material will be affected to the efficiency and the reflectance coating.

***Key word**: Silicon Oxide Silicon Nitride, Anti-Reflection Coating (ARC), Efficiency, Reflectance*

1.0 INTRODUCTION

Silicon is the most commonly used semiconductor in solar cells nowadays. It is a chemical element, which has the symbol Si and atomic number 14. Solar cells are made of various semiconducting materials. The direct conversion of sunlight into energy using solar cells is called the photovoltaic effect [3]. The word photovoltaic is a combination of the Greek word for light and the name of the physicist Allesandro Volta. The conversion process is based on discovery by Alexander Bequerel in 1839[2,3]. The photoelectric effect describes the release of positive and negative charge carriers in a solid state when light strikes its surface.

Efficiency of a solar cell and its lifetime can be raised by coating the light sensitive surface of the cell with an anti reflection coating (ARC) [4] ARC reduces the reflectance of the light incident radiation on the cell surface and also protects it from radiations and atmospheric effects. In the past, different anti reflection coating have been optimized theoretically and experimentally on bare or encapsulated cells. Much research has been reported on layer anti-reflection coating, where different type of materials was use such as SiO2/TiO2 and ZnS/MgF.

In this research an analysis of single layer and dual layer silicon dioxide and silicon nitride for commercial solar cells fabricated on multicrystalline silicon wafers has been carried out. The research mainly focuses on the concept of utilizing the single and double layer-graded refractive index silicon dioxide (SiO2) and silicon nitride (Si_3N_4) analysis the reflection losses in the spectrum of interest.

2.0 OBJECTIVES

- To analysis about the ARC characteristics.
- To aims minimize the reflection losses in the spectrum of interest using silicon dioxide and silicon nitride with different wavelength.
- To observe the high efficiency and low reflectance of different silicon structured layer and thickness using Silvaco Atlas simulator.

3.0 SCOPE OF WORK

This research was conducted by using Silvaco Atlas device as simulation software to analysis single and dual layer silicon oxide and silicon nitride anti reflection coating for Si solar cell due to higher efficiency and lower reflectance. The processes involved analyzing spectral response, characterizing the efficiency and reflectance of Si solar cell. In the designing process, anti reflection coating for Si solar cell was simulated using Atlas.

There were three types of ARC that have been analyzed. There are single layer anti reflection coating, dual layer anti reflection coating and combination layer silicon dioxide and silicon nitride layer of anti reflection coating for Si solar cell.

In single layer antireflection coating, silicon nitride (Si_3N_4), and silicon dioxide (SiO_2) was chosen as a fundamental material in the ARC layer. Then the ARC layer will be analyzed using spectral response analysis. With the suitable wavelength get from reference, the experiment will do in 6 different wavelength, refractive index and thickness. In the spectral response analysis, current affect such as source photocurrent and available photocurrent will be observed. The most important part in this research was to obtain the efficiency and reflectance of anti reflection coating. All the experiment will overlay the graft to see the different between the each other.

In dual layer, silicon nitride (Si_3N_4) and silicon dioxide (SiO_2) was chosen as an ARC layer. Processes of characterizing the ARC layers are similar to single layer ARC. However, dual layer ARC involved two layer of anti reflection coating with same material but difference properties such refractive indices and wavelength. The dual layer ARC thickness is identical to single layer ARC in order to demonstrate better efficiency and smallest reflectance.

In combination layer of ARC silicon nitride (Si_3N_4) and silicon dioxide (SiO_2) was chosen as an ARC layers. Combination of ARC involved two layer of anti reflection coating with difference material. In this experiment, the thickness of combination layer of ARC is exactly similar dual layer ARC.

4.0 MATERIAL

Silvaco ATLAS is a physically based device simulator that predicts the electrical characteristic that are associated with specified physical design and bias conditions. [2] Physically based simulation is very different from analytical modeling that provides insight, or predictive capabilities, or encapsulation of the theoretical knowledge. Figure 1 and figure2 shows refractive index curve of silicon dioxide (SiO_2) and silicon nitride (Si_3N_4). From the curve maximum refractive index and maximum wavelength will get. The value of the wavelength and refractive index will use to calculate the thickness of material. Equation 1 will use for single layer and equation 2 for double layer.

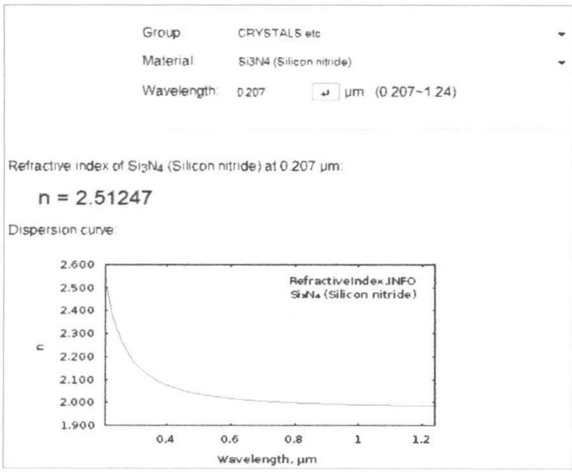

Figure 1: Refractive index curves of silicon nitride (Si_3N_4)

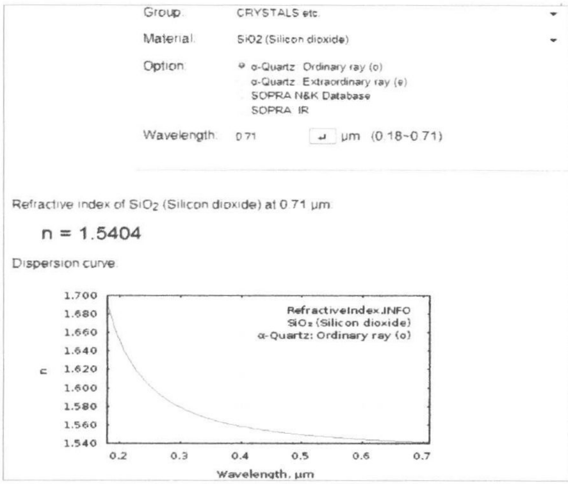

Figure 2: Refractive index curves of silicon dioxide (SiO_2)

5.0 METHODOLOGY & DESIGN PROCESS

5.1 Anti Reflection Coating

Anti reflection coating (ARC) with angle and wavelength independent reflection and robust manufacturing process are vital in achieving high performance cost effective solar cells. [5] Typically a quarter wavelength single layer thin film ARC is applied to solar cells to increase efficiency and reduced reflectivity in limited spectral range under surface normal incident light conditions. Since at high refractive indices (>2.4 at 640nm) these layer of ARC become highly absorbing, the bottom layer refractive index should be greater than upper layer refractive index. [1, 6] Various optical designs and surface texturing structures were reported for improved cell efficiencies.

5.1.1 Single Layer Anti Reflection Coating

A quarter wavelength thickness of ARC layer *effectively reduces the reflection to a minimum at* normal incidence. The optimal thickness for minimum reflection at wavelength λ is defined by the equation 1.

$$d = \frac{\lambda}{4n} \quad (1)$$

Where,
d - Optimal thickness of the layer
n – Refractive indices of the material
λ – Wavelength of the material
For a λ/4 thick coating on Si the reflectance is given by the general equation 2.

$$R = \left(\frac{n_0 n_{si} - n_1^2}{n_0 n_{si} + n_1^2}\right)^2 \quad (2)$$

Where,
$n_1$is refractive indices of the material layer.
no and nsi are refractive indices of air and silicon respectively.

The necessary and sufficient conditions for a single-layer coating to produce zero reflectance are calculated based on equation 3.

$$n_1 = (n_0 n_{nsi})^{1/2}; n_1 < n_{si} \quad (3)$$

5.12 Dual Layer Anti Reflection Coating

It is known that at normal incidence, a quarter wavelength thick material layers effectively reduce the reflection to minimum. The thicknesses of each layer in terms of their refractive indices are calculated based on equation 4.

$$d_1 = \frac{\lambda}{4n_1};\ d_2 = \frac{\lambda}{4n_2} \quad (4)$$

d_1 and d_2 are optimal thickness of the top and bottom layers respectively. The required refractive indices for the top and bottom layers of the dual layers silicon nitride coating are given by the equations 5.

$$R_1 = \left(\frac{n_0 n_2 - n_1^2}{n_0 n_2 + n_1^2}\right)^2 ; R_2 = \left(\frac{n_1 n_{si} - n_2^2}{n_1 n_{si} + n_2^2}\right)^2 \quad (5)$$

Where,
R1 - reflectance of the top layer (L1)
R2 - reflectance of the bottom layer (L2)

n_1 and n_2 are the refractive indices of the top and bottom layers respectively.
no and nsi are refractive indices of air and silicon respectively.

The necessary and sufficient conditions for a dual-layer coating to produce zero reflectance are calculated based on equation 6.

$$n_1^3 = n_o^2 n_{si} \quad ; \quad n_2^3 = n_o n_{si}^2 \quad (6)$$

5.2 MODELING

ATLAS device simulator by Silvaco International was introduced for used as a tool in modeling solar cell. This simulator will demonstrate the construction of silicon region, specification of normally incident light beam, definition of anti-reflective layer using the INTERFACE statement and the simulation of spectral response. [2] The spectral response and external quantum efficiency of no antireflection coating (ARC), single layers SiO_2-Si_3N_4ARC and double layers SiO_2 - Si_3N_4 ARC were analyzed in this project. ATLAS produces three types of output. Run time output is provided in the bottom of the DECKBUILD window. If run as a batch job, the run-time output can be stored to a file. Errors occurring in the run-time output will be displayed in this window. Note that not all errors will be fatal (as deck build tries to interpret the users file and continue). This may cause a statement to be ignored, leading to unexpected results. It is recommended that the user check the run-time output of any newly created input file, the first time it is run, to intercept any errors.

Simulation of ARC and simulate the spectral response of variable coating thickness by using ATLAS simulator. The mesh of solar cell has been created, and then the substrate material is setting up to silicon. The doping concentration of boron is fixed to 1x 10^{14} atom cm^{-2} of n-type. In this analysis, the beam is fixed to 90º angle and the ARC layer is setting the thickness to plot the spectral response graph. Only using the ATLAS simulator can do the ARC simulation by producing spectral response graph to calculate the efficiency and reflectance.

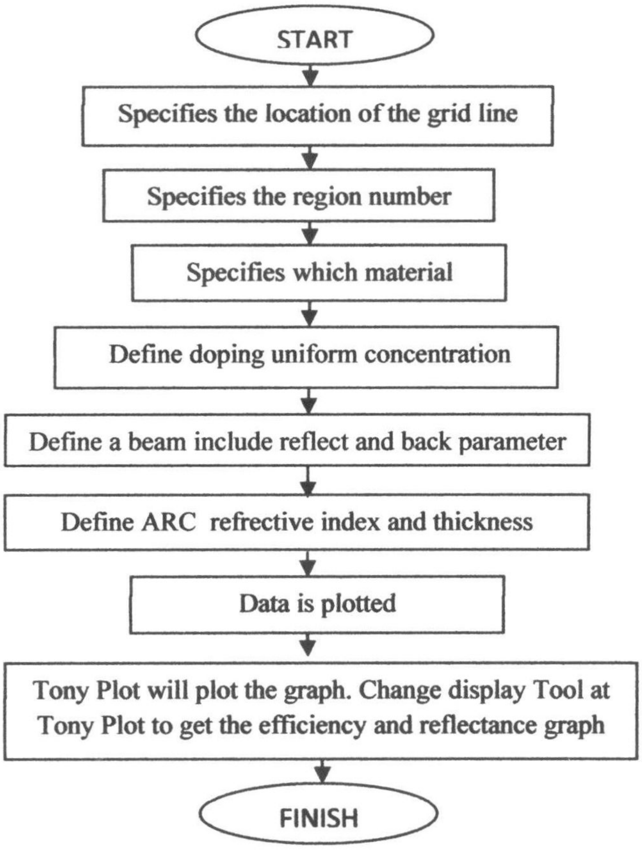

Figure 3: .Flow chart simulate anti reflection coating (ARC) using ATLAS

5.2.1 Spectral Response Analysis

ATLAS was used to simulate the spectral response of the solar cell. In the analysis, a different light beam is required to vary the wavelength. The range of wavelength used was 300nm to 1000nm. The plot of source photocurrent (current available in the light beam) and available photocurrent (current available for collection) versus wavelength shows how the device behaves. The source photocurrent can be defined as the amount of current generated by the light source. The available photocurrent is the amount of current absorbed by the semiconductor. Differences between these two are due to reflection, transmission or absorption in non-semiconductor materials. Solar cells with lowest reflection and highest transmission can give the high efficiency. A critical goal for photovoltaic energy conversion is the development of high efficiency with low reflectance. By using Tony Plot function, the x-axis was set to be optical wavelength and the y-axis as the efficiency. Basically, the efficiency is defined as power output/power input and the reflectance is defined as power input – power output. As mentioned earlier that the research is to observe the effect of ARC on solar cell efficiency and reflectance. Therefore, plot of efficiency versus wavelength and reflectance versus wavelength are important. By using Tony Plot function, the efficiency and reflectance can be plotted using:

$$\text{Efficiency, } \eta = \frac{\text{Available Photocurrent}}{\text{Source Photocurrent}} \qquad (7)$$

$$\text{Rerlectance} = \text{Source Photocurrent} - \text{Available Photocurrent}$$

6.0 RESULTS & DISCUSSION

Listed below is the result of modeling using Atlas simulator tools. Solar cells that use antireflection coating (ARC) improved their efficiency. Antireflective coatings are important in order to reduce the reflection of light so that more light can be absorbed by the solar cells. The material used for AR coating also important to give the lowest reflection in improving the efficiency. The ratio of available/source photocurrents is often known as external quantum efficiency. The source photocurrent is the amount of current generated by the light source and the available photocurrent is the amount of current absorbed by the semiconductor. By comparing the plot of the cases with and without AR coating, solar cell with ARC is more efficient.

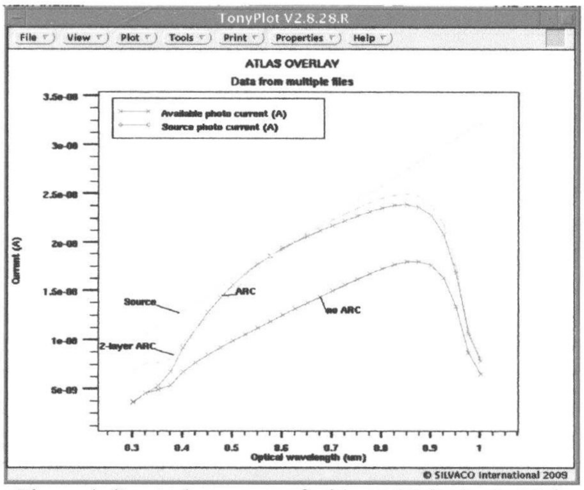

Figure 4: Spectral response of without ARC, single ARC and double ARC measured by Silvaco Atlas device simulator.

6.1 SINGLE LAYER ANTI REFLECTION COATING

6.1.1 Single Layer Silicon Oxide ARC

For a single layer anti reflection coating the efficiency and reflectance curve is resulting in a Figure 5 and 6. The wavelength for the silicon dioxide is (0.18 - 0.71) μm and the refractive index can search through the refractive index curve for SiO_2. (Figure 2) The thickness will be calculated using equation 1. A maximum efficiency=0.950 and reflectance= 1.15e-11 at wavelength 0.71 μm of SiO_2 can be reached with refractive index n=1.54066 and thickness d=0.11358 μm.

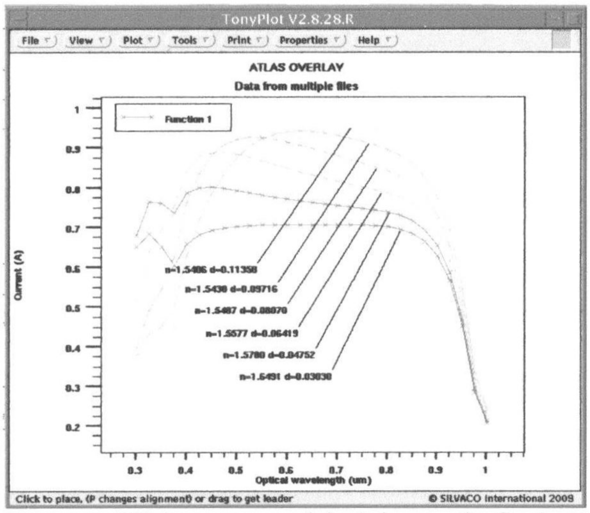

Figure 5: Efficiency curves of single layer anti reflection coating measured by Silvaco Atlas device simulator.

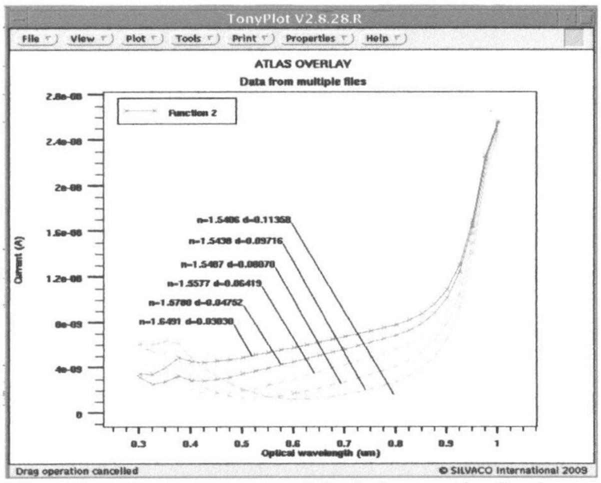

Figure 6: Reflectance curves of single layer anti reflection coating measured by Silvaco Atlas device simulator

Figure 5 and 6 shows when the value of wavelength increases the value of efficiency also increased and reflectance value becomes small.

Table 1 show the value of the difference wavelength will affect the index of refraction of SiO2 layer anti-reflection coating and measurement efficiency and reflectance values measured using Silvaco ATLAS.

Table 1: Efficiency and reflectance listed with respect to chosen single layer SiO_2 anti reflection coating.

λ (μm)	Refractive index n	Thickness d (μm)	Efficiency η	Reflectance R
0.2	1.64901	0.0303	0.706	3.42e-09
0.3	1.57802	0.04752	0.798	2.53e-09
0.4	1.55772	0.06419	0.888	1.62 e-09
0.5	1.54875	0.08071	0.924	1.25 e-09
0.6	1.54382	0.97160	0.941	1.15 e-09
0.7	1.54066	0.11358	0.950	1.15 e-09

6.1.2 Single Layer Silicon Nitride Anti Reflection Coating

For a single layer silicon nitride anti reflection coating the efficiency and reflectance curve is resulting in a Figure 7 and 8. The wavelength for the silicon nitride is (0.207 – 1.24) μm and the refractive index can search through the refractive index curve for Si_3N_4 in figure 1. The thickness will be calculated by using equation 1. A maximum efficiency for this analysis is 0.997 and reflectance 2.71e-11 at wavelength 0.6 μm of Si_3N_4can be reached with refractive index n=2.01487 and thickness d=0.07444 μm.

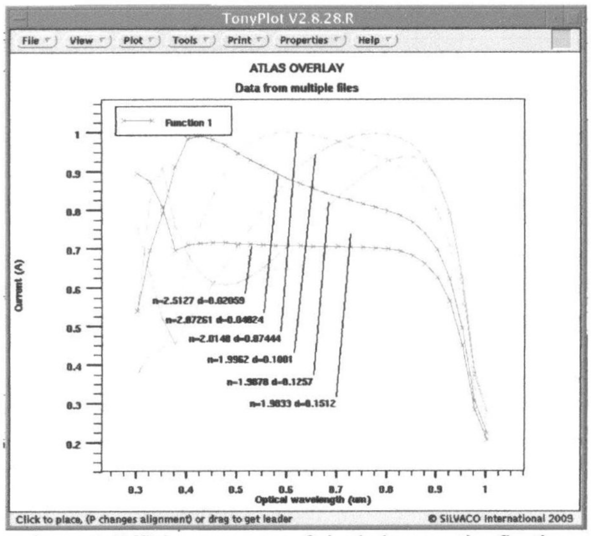

Figure 7: Efficiency curves of single layer anti reflection coating measured by Silvaco Atlas device simulator

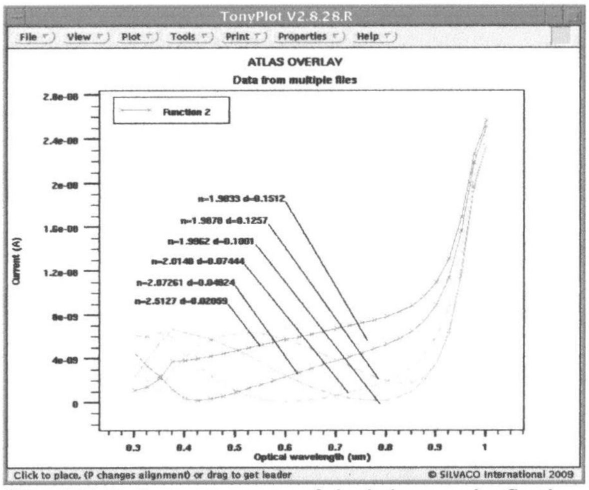

Figure 8 : Reflectance curves of single layer anti reflection coating measured by Silvaco Atlas device simulator

From the analysis single layer silicon nitride ARC have higher efficiency and low reflectance compared to the single layer silicon dioxide. Table 2 demonstrated the different value of wavelength will affected the refractive index of Si_3N_4 single layer anti reflection coating. All efficiency and reflectance values measured with the Silvaco ATLAS.

Table 2: Efficiency and reflectance listed with respect to chosen single layer Si_3N_4 anti reflection coating.

λ (µm)	Refractive index n	Thickness d (µm)	Efficiency η	Reflectance R
0.207	2.51277	0.02059	0.893	1.06 e-09
0.4	2.07261	0.04824	0.991	1.04 e-09
0.6	2.01487	0.07444	0.997	2.71 e-11
0.8	1.99622	0.10018	0.996	9.17 e-11
1.0	1.98783	0.12576	0.935	9.97 e-10
1.2	1.98334	0.15126	0.968	4.33 e-10

6.2 DOUBLE LAYER ANTI REFLECTION COATING

6.2.1 Double Layer Silicon Dioxide

For a double layer of silicon dioxide, the highest efficiency and the lowest reflectance can be obtained with configuration of $n_{top} = 1.665$, $n_{bottom} = 1.665$, and $d_{top} = 0.02987\mu m$, $d_{bottom} = 0.02987\mu m$. With that configuration, the efficiency is 0.919 while the reflectance is 1.15e-09A. It is seen that the efficiency of both the quarter wavelength of dual layer SiO_2 first increase rapidly and then decrease again after passing a maximum.

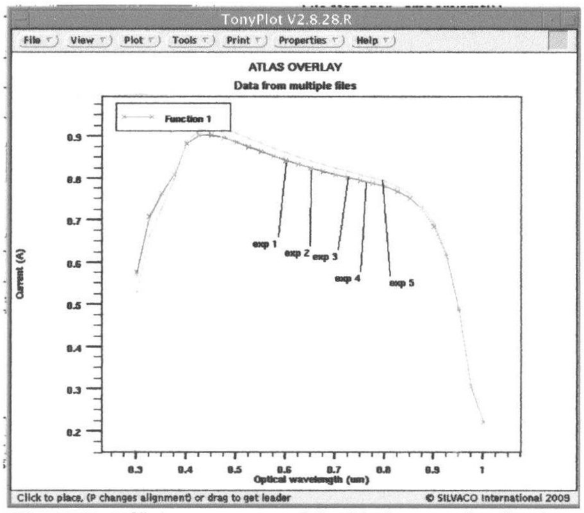

Figure 9 : Efficiency curves of double layer anti reflection coating measured by Silvaco Atlas device simulator

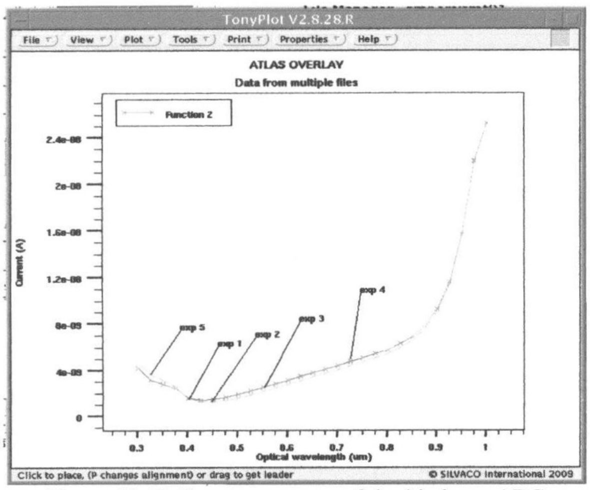

Figure 10: Reflectance curves of double layer ARC measured by Silvaco Atlas device simulator

At wavelength 0.43µm curve shows the maximum value of efficiency and after that the graph started a decline. Not much difference between experiments 1 to 5 in terms of forms of graphs.

Table 3: Efficiency and reflectance listed with respect to chosen double layer silicon dioxide anti reflection coating.

Exp	λ (µm)	Refractive index (n)	Thickness (d) µm	Eff (η)	Reflectanc (R)
Ex1	0.207	1.645	0.0303	0.901	1.33 e-09
	0.181	1.685	0.0268		
Ex2	0.197	1.650	0.0298	0.902	1.32 e-09
	0.183	1.680	0.0273		
Ex3	0.196	1.655	0.0296	0.904	1.29 e-09
	0.186	1.675	0.0277		
Ex4	0.193	1.660	0.0291	0.905	1.30 e-09
	0.187	1.670	0.0280		
Ex5	0.199	1.665	0.0298	0.919	1.15 e-09
	0.199	1.665	0.0298		

6.2.2 Double Layer Silicon Nitride

An ideal double layer silicon nitride ARC requires an optimum values of d_{top} = 0.0348µm, d_{bottom} =0.0235µm and n_{top} = 2.15, n_{bottom} = 2.39. Figure shows the efficiency and reflectance curve for double layer silicon nitride ARC.

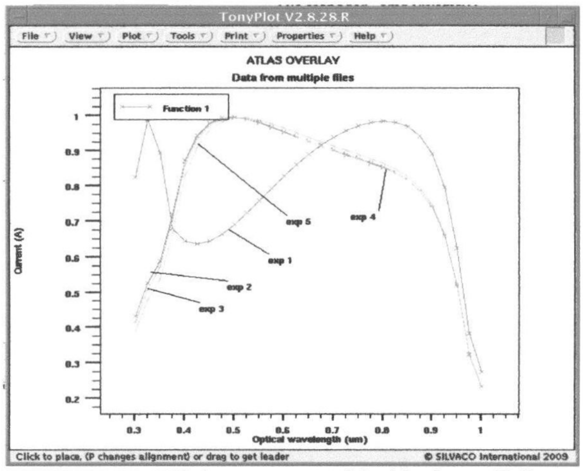

Figure 11: Efficiency curves of double layer ARC measured by Silvaco Atlas device simulator

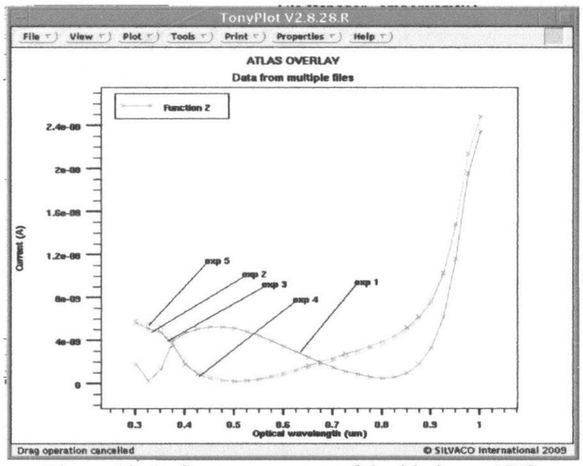

Figure 12: Reflectance curves of double layer ARC measured by Silvaco Atlas device simulator

Table 4 demonstrated five experiments of dual layer silicon nitride anti reflection coating with difference thickness and refractive index for each layer of ARC. Both experiment get almost nearest value for efficiency and reflectance.

Table 4: Efficiency and reflectance listed with respect to chosen double layer silicon dioxide anti reflection coating.

Exp	λ (μm)	Refractive index (n)	Thickness (d) μm	Eff (η)	Reflectance (R)
Ex1	0.740	2.00	0.0925	0.985	1.43 e-10
	0.207	2.51	0.0206		
Ex2	0.300	2.15	0.0348	0.994	9.97 e-10
	0.225	2.39	0.0235		
Ex3	0.280	2.20	0.0318	0.993	1.17e-10
	0.234	2.34	0.0250		
Ex4	0.296	2.18	0.0340	0.992	1.10e -10
	0.227	2.36	0.0241		
Ex5	0.276	2.21	0.0313	0.991	1.21 e-10
	0.248	2.28	0.0272		

6.3 COMBINATION OF ANTI REFLECTION COATING

6.3.1 Combination silicon nitride and silicon dioxide

For a double layer containing silicon nitride and silicon dioxide the highest efficiency and the lowest reflectance was obtained with configuration of n_{top} = 1.688, n_{bottom} = 2.40, and d_{top} = 0.0306um, d_{bottom} = 0.0274um at experiment 5.

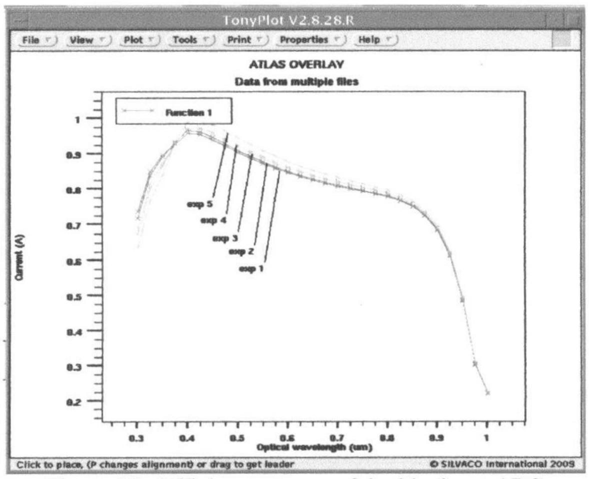

Figure 13 : Efficiency curves of double layer ARC measured by Silvaco Atlas device simulator

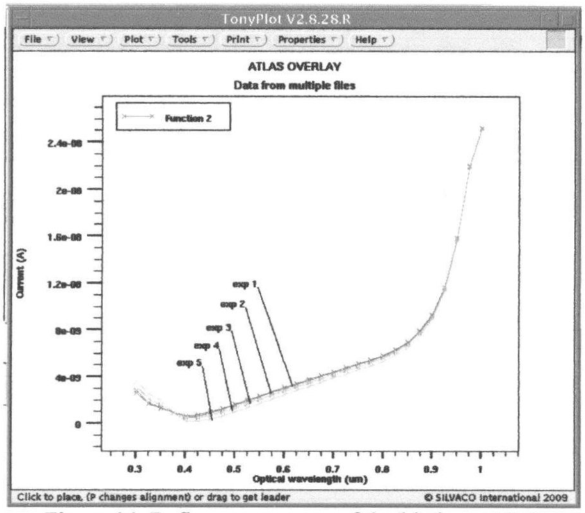

Figure 14: Reflectance curves of double layer ARC measured by Silvaco Atlas device simulator

Table 5: Efficiency and reflectance listed with respect to chosen combination of silicon nitride and silicon dioxide anti reflection coating.

Exp	λ (μm)	Refractive index (n)	Thickness (d) μm	Eff (η)	Reflectanc (R)
Ex1	0.243	1.605	0.0378	0.955	5.78 e-10
	0.208	2.50	0.0208		
Ex2	0.241	1.615	0.0348	0.964	4.76 e-10
	0.220	2.42	0.0230		
Ex3	0.219	1.625	0.0337	0.967	4.28 e-10
	0.231	2.35	0.0246		
Ex4	0.212	1.635	0.0324	0.971	3.77 e-10
	0.239	2.32	0.0258		
Ex5	0.207	1.688	0.0306	0.987	1.43 e-10
	0.263	2.40	0.0274		

7.0 CONCLUSION

Since the refractive index of silicon is relatively high, its surface reflects a high portion of the light incident radiation throughout the spectral range between 300 and 1000 nm. The way to reduce this high reflectance is to coat the surface of semiconductor with at least a single layer of one-quarter optical thickness. By used of single layer ARC, this research has obtained a decrease in reflectance of the light incident radiation. The thickness gives an effect on solar cell efficiency. By comparing the plot of the cases with and without AR coating, solar cell with ARC is more efficient. Single layer ARC does not minimize reflectance over a large range of wavelengths although they have potential to reduce reflection dramatically compared to a bare silicon surface. Silicon Nitride films with high refractive index are known to absorb at short wavelengths.

These results demonstrate that silicon nitride, can be used to increase the efficiency of the solar cell and decrease the reflection losses to a minimum in a limited way compare to the silicon dioxide. Double layer silicon nitride ARC can be used to increase the efficiency of the solar cell and decrease the reflection losses to a minimum in a limited way compare to single layer and double layer with different material. From the curve of double layer silicon nitride and silicon dioxide ARC, the thickness used will give the same curve form and not more differences in terms of value efficiency and reflectance.

By used of ARC, this research has obtained a decrease in reflectance of the light incident radiation. Silicon nitrides and their alloys represent a very special class of materials. Solar cell simulation could be useful for time saving and cost consumption. This method also cheaper and faster compared to experimental. So the simulation has some advantages than physical experimental to made decision to fabricate a solar cell.

8.0 FUTURE DEVELOPMENT

One type of future development focuses on the development of cells that convert increased levels of the incoming photons to electricity. These would take less incoming energy to begin releasing electrons and would also capture more of their specific wavelength of the light spectrum. There is currently a lot of research on going in this field dealing with making the light rays diffract to increase absorption rates. Normally the rays will reflect of the backing material and travel out of the cell. By creating a lower angle of exit more energy can be absorbed by the cell.

Another approach to reduce reflection is to use textured surfaces. These are produced by etching the silicon surface with an etch that etches silicon much more rapidly in one direction through the crystal structure than another. In terms of Miller indices, the silicon surface for textured cells is normally aligned parallel to a (100) plane and the pyramids are formed by the intersection of (111) planes. Dilute caustic soda (NaOH) solutions are a commonly used selective etch.

If an antireflection coating is used, reflection of sunlight can be kept well below 3%. Even without an antireflection coating, the reflection when embedded in a material of refractive index similar to glass is only about 4%. Another desirable feature is that light is coupled into the silicon at an angle which ensures that it will be absorbed closer to the surface of the cell. This will increase the probability of its collection, particularly for the more weakly absorbed long wavelengths.

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