EFFECTS OF DOUBLE LAYER ANTI-REFLECTION COATING ON OPTICAL PROPERTIES AND ELECTRICAL FACTORS OF BLACK SOLAR CELLS

Warakorn Limsiri[1], Thipwan Fungsuwannarak[1,2,*], Kamonchanok Mekmork[1,3], Supanut Laohawiroj[1], Nikhil Jaden Naidoo[1] and Peerawoot Rattanawichai[1]

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Abstract

Solar cell coated with an anti-reflection coating (ARC) is essential for quantum efficiency improvement and light-absorbing increase. The advantage of a double layer anti-reflection coating (DLARC) to form a black solar cell with gradient index results in effective anti-reflectance. In this simulation work, the OPAL-2 simulatio predicts the minimizing optical losses of various ratio thickness of DLARC layer (silicon oxynitride (SiN_xO_y) and silicon nitride (SiN_x). It was found the optimal SiN_xO_y: SiN_x ratio thickness of 0.5:0.5 to enhance the photogenerated current with a weighted reflectance (between 400 and 700 nm) around 2.03 %. In this experimental work, PV cells with SiN_xO_y/SiN_x DLARC were fabrication in the mass-scale production by varying the total thickness of DLARC layer (83-176 nm) under the optimal DLARC ratio thickness. The DLARC layer was deposited by a plasma-enhanced chemical vapor deposition (PECVD) technique to produce the refractive index of SiN_xO_y and SiN_x, of 1.74 and of 2.04, respectively. In the solar cell production process, short-circuit current values of all-black solar cells are increased by 4.17% as compared with a blue solar cell under the same firing-electrode condition. However, it was found that the decreased fill factor values of all-black solar cells in this condition are associated with more DLARC thickness, which also causes poor electrode quality such as high series-parasitic resistance. In this work, DLARC thickness of 143 nm obtains a power conversion efficiency of 18.24%, with a gain improvement of 0.53%, compared to blue PV cells coated by a single SiN_x layer with 83 nm thickness.

Keywords: **Blue solar cell, black solar cell, OPAL-2 Simulation, antireflection coating, gradient-index**

Introduction

The appropriate solar cell requires an anti-reflection coating (ARC) layer to suppress undesired interfacial Fresnel reflections, which leads to zero reflection at a single wavelength. The broadband wavelength of minimizing surface reflectance needs in photovoltaic (PV) application. Thus, there are many

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[1] *School of Electrical Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand. E-mail: thipwan@g.sut.ac.th*

[2] *Research Network NANOTEC-SUT on Advanced Nanomaterials and Characterization, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand.*

[3] *Solartron Public Company Limited, Nakhon Ratchasima, 30130, Thailand.*

[*] *Corresponding author*

research groups to have already suggested several techniques based on a multilayer stack of ARC (Chen and Wang, 2011; Seiffe *et al*., 2011; Kim *et al*., 2013; Alexander and May, 2020). In electronic mechanisms, the ARC film can be functional as a surface passivation layer to reduce the carrier recombination rate, which can increase the current collection on the cell surface (Dupuis *et al*., 2009). Currently, the fabrication of a double layer anti-reflection coating (DLARC) has been studied from silicon alloys such as SiN:H/SiO_2, SiN_x/SiN_x and SiO_xN_y/SiN_x (Chen and Wang, 2011; Seiffe *et al*., 2011; Kim *et al*., 2013; Alexander and May, 2020). The DLARC film layer can reduce light reflectivity and increase the current generation by 2% compared with a single SiN_x layer because of an increase of the photon penetration into the solar cells (Chen and Wang, 2011).

However, the optimized adjustment of optical properties such as reflectance, transmittance, optical index, and thickness of the DLARC film in the term of the fabrication process is not widely studied. This article has focused on the fabrication of SiO_xN_y/SiN_x DLARC by adjusting the thicknesses. OPAL-2 simulation was demonstrated for determining the maximize photocurrent generation in the conditions of thickness ratio of SiO_xN_y/SiN_x. The DLARC film of the combination of SiO_xN_y film and SiNx film can be a surface passivation layer on silicon cells. Therefore, careful adjustment of the multilayer thickness has been done by a plasma-enhanced chemical vapor deposition (PECVE) technique. A refractive index value of SiO_xN_y film and SiN_x film is in the range of 1.45 to 1.9 (Park *et al*., 2017) and 1.8 to 3.2 (Santana and Morales-Acevedo, 2000) respectively. The thickness and refractive index of the film are measured by the Ellipsometer. The reflection coefficient is analyzed by UV-Visible Spectroscopy, model Cary Series UV-Vis Spectrophotometer, Agilent Technologies. In addition, program OPAL-2 was used for calculating photo generation current of PV cells with permitting ARC optimization via maximizing photocurrent for increasing the efficiency of PV cells on an industrial scale (Rudzikas *et al*., 2020).

Experiment Details

Fabrication

The substrate with size 156×156 mm^2 and 200 microns thickness used in this work is a multi-crystalline silicon p-type (mc-Si) doped with boron. The electrical resistance of the substrate has a range of 1-3 ohm-cm. The procedure steps of PV cells with DLARC film were shown in Figure 1.

Firstly, the surface of mc-Si sheets was etched by HF/HNO_3 solution at 8-12°C to roughen the surface. The concentration of HF/HNO_3 solution was controlled at 5% and 20%, respectively. After that, the p-n junction was created by phosphorus diffusion in the surrounding temperature at 780-840°C for 15 min, to form the n-type layer with sheet resistivity of 95 ohms per square centimeter which are measured by the 4-point probe technique. Then, the side surface of n-type Si was etched by HF solution with a concentration of 9.5% to protect the side short circuit and to remove the phospho-silicate glass (PSG) that obtain inevitably from the phosphorus diffusion process. In the PECVD process, DLARC films were coated on the front-side of the n-Si surface through the conveyor belt at the adjustable speed from 200 to 307 cm/min to control their film thicknesses. The PECVD used the gas mixture with the different ratio between silane gas (SiH_4) and ammonia gas (NH_3) for SiN_x layer and silane gas (SiH_4) and nitrous oxide (N_2O) for SiN_xO_y layer at the pressure of 0.25 mbar and temperature of 400°C. After the PECVD process, a screen-

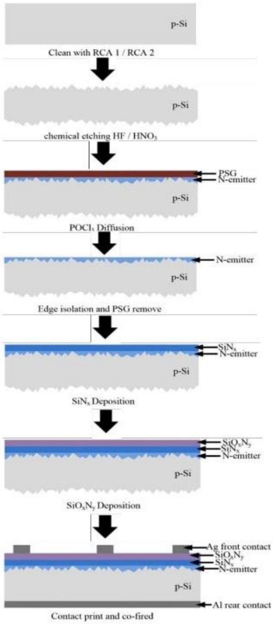


Figure 1. **Fabrication process of PV cells with DLARC film**

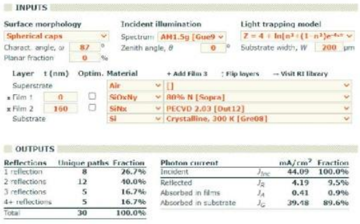
printing technique was used for metal contact production, silver and aluminum metals were are a grid electrode and a rare electrode for n-Si and p-Si of PV cell, respectively. The PV cells were taken part in the fast-firing process with a temperature of 890°C to reduce the resistance of contact with an excellent ohmic contact between the metal contact and silicon.

Electrical properties of PV cells were analyzed by Solar LED lamp simulation at the wavelength range of 370-1,100 nm with, the light intensity of 1,000 W/m^2 (AM1.5) and the temperatures at 25°C. In this mass-production scale, 150 PV cells were produced in each thickness condition. A PV cell in each condition was selected randomly for the characterizations including thickness, refractive index, and the coefficient of reflection.

Results and Discussion

Set-up Parameters in OPAL Simulation

Freeware program OPAL-2 is a rapid optical simulation of silicon solar cells to compute the optical losses associated with the front surface of a Si solar cell. In this paper, OPAL-2 was set-up the functionality to include any illumination angle of incidence and polarization with AM1.5g, spherical caps, which have been demonstrated to approximate isotextured polycrystalline Si with charater angle of 87 degree. PECVD technique 2.03 (Dut12) and 80% N (Sopra) were selected for the first SiN$_x$ film and SiN$_y$O$_x$ film, respectively. Both films were adjusted from 0 to 160 microns on the 200 microns substrate width. PECVD technique 2.03 (Dut12) and 80% N (Sopra) were selected for the first SiN$_x$ film and SiN$_y$O$_x$ film, respectively. The parameters were keyed in the OPAL:2 program as shown in Figure 2.



INPUTS

Surface morphology: Spherical caps
Charact. angle, α: 87 °
Planar fraction: 0 %
Incident illumination
Spectrum: AM1.5g [Gue9
Zenith angle, θ: 0 °
Light trapping model: Z = 4 + ln[n² + (1 - n²)e^-4ᵃᵂ
Substrate width, W: 200 µm

Layer	t (nm)	Optim.	Material	
Superstrate			Air	[]
Film 1	0	☐	SiOxNy	80% N [Sopra]
Film 2	160	☐	SiNx	PECVD 2.03 [Dut12]
Substrate			Si	Crystalline, 300 K [Gre08]

OUTPUTS

Reflections	Unique paths	Fraction
1 reflection	8	26.7%
2 reflections	12	40.0%
3 reflections	5	16.7%
4+ reflections	5	16.7%
Total	30	100.0%

Photon current		mA/cm²	Fraction
Incident	J_{inc}	44.09	100.0%
Reflected	J_R	4.19	9.5%
Absorbed in films	J_A	0.41	0.9%
Absorbed in substrate	J_G	39.48	89.6%

Figure 2. Parameters setting for OPAL 2 freeware

Figure 3 depicts the relationship between photocurrent absorbtion and the optical loss of the ratio of SiNx and SiOxNy layer on the Si solar cells, as determined by OPAL 2. The decrease of SiNx ratio from 1 to 0.5 shows the slightly increase of the photocurrent absorbtion in the samples, while the reduction of optical loss is found, however, the photocurrent absorbtion decreases with a rise in optical loss when the SiNx ratio decreases from 0.5 to 0. It is noticed that a ratio of 0.5:0.5 between SiNx and SiOxNy provides the highest photocurrent absorption in samples and effectively lowers optical loss.

Optical Properties: OPAL-2 Simulation

The sample are defined fabricate with SiO$_x$N$_y$: SiN$_x$ ratio of DLARC layers by OPAL-2 in Table 1 shows the photocurrent generation of the PV cells including photocurrent incident (J_{INC}), photocurrent reflected (J_R), photocurrent absorbed in the DLARC film (J_A), and photocurrent absorbed in the substrate (J_G). The OPAL-2 simulation prediction is found the 3.67% minimizing optical losses of SiNxOy: SiNx ratio of 0.5:0.5 to enhance the photogenerated current with a weighted reflectance around 2.03%. The minimizing reflectance wavelength at 660 nm

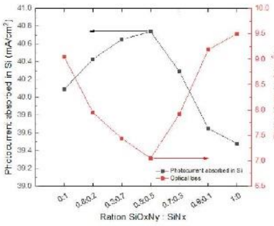


Figure 3. Calculated photocurrent absorbed in p-n Si bulk and optical loss of the samples using OPAL-2 simulation

Table 1. Calculated photocurrent generation of PV cells in the various SiOxNy: SiNx ratio of DLARC layers by OPAL-2 program

Simples	Thickness		Photo current (mA/cm^2)			Optical loss (%)	Weight reflectance (%)
	SiN$_x$	SiO$_x$N$_y$	Reflected	Absorbed in ARC	Absorbed in P-N Si	J_R/J_{in}	%WR from 400-700 nm
1	0	160	3.99	0	40.09	9.05	12.75
2	32	128	3.57	0.09	40.43	7.95	11.34
3	48	112	3.28	0.16	40.65	7.44	10.04
4	80	80	3.11	0.24	40.74	7.05	8.82
5	112	48	3.49	0.31	40.29	7.92	9.92
6	144	16	4.05	0.38	39.65	9.19	10.95
7	160	0	4.19	0.41	39.48	9.50	10.80

Table 2. Refractive index values of DLARC films with the different total DLARC thicknesses on p-n Si substrates

Group	Belt speed (cm/min)	Thickness (nm)			Refractive index	
		SiN_x	SiO_xN_y	Total	SiN_x	SiO_xN_y
A	205	82.32	94.56	176.88	2.00	1.62
B	230	76.12	81.57	157.69	2.01	1.69
C	256	70.95	71.93	142.88	2.04	1.76
D	282	67.61	66.51	134.12	2.07	1.79
E	307	61.95	66.29	128.24	2.09	1.83
F	200	83.00	-	83.00	2.08	-

is shifted onto shorter wavelength region with an increase in SiO_xN_y fraction of DLARC layer (Rudzikas *et al*., 2020; McIntosh and Baker-Finch, 2012).

The Optical Properties of the Produced DLARC Layer

Table 2 details the reflective index and thickness of DLARC films with SiN_x:SiO_xN_y ratio thickness of 0.5:0.5 (Wang *et al*., 1974). The total DLARC thicknesses were adjusted about 176-128 nm depending on an increase in the speed of conveyor belt of PECVD process. The decrease of SiO_xN_y thickness strongly depends on the increasing change of its refractive index from 1.62 to 1.83, while the r-efractive index of SiN_x slightly decreases from 2.09 to 2.00 with a decrease in SiN_x thickness. This refractive index arrangement provides the appropriate DLARC film on PV cells for reducing the sun light reflection and enhancing the photon absorption.

Table 3. %WR of DLARC films on the surface of PV cells with the different thickness compared with single SiNx film

Sample	Weight Reflectance (%WR) at wavelength range		
	280-550 nm	550-800 nm	280-800 nm
A	4.58	5.74	5.13
B	4.94	5.93	5.41
C	5.56	5.05	5.31
D	5.63	4.62	5.14
E	5.33	4.26	4.81
F	6.92	4.17	5.60

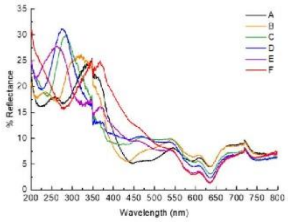


Figure 4. Reflectance of DLARC films on the surface of PV cells with the different thickness

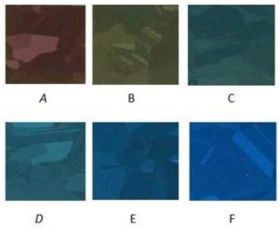


Figure 5. The change of PV cell colors with the different DLARC thicknesses

Figure 4 showed the measured reflectance (%R) of DLARC film in in wavelength between 200-800 nm. The minimizing reflectivity occurring at 2 wavelengths in the visible range achieved through SiO_xN_y:SiN_x DLARC layer.

The Refractive index is a property of material. It doesn't depend upon glass thickness. Refractive index is one of optical constants for a material. SiNx not related to thickness because where the thickness changes, the refractive index not change much (steady values) on the other hand SiOxNy is change as a result of process fabrication.the lowest %R of both SiN_x ARC and DLARC shows the wavelength around 640 nm but the DLARC film provides another second low point of %R at around 430 nm. The %WR values at 200-800 nm wavelength of all DLARC samples are less than that of single SiN_x ARC in particular the range of 280-550 nm (blue light region) as detailed in Table 3. It seems that 83 nm SiN_x ARC sample from calculated and measured have difference %WR because of the equivalent of material setting parameters such as type of microcrystalline Si and texture surface. However, the increase of DLARC thickness shows an increase in %WR at 500-800 nm (Orange light region). The low %R at a blue light region of DLARC samples with various thicknesses can imply directly to the color of the DLARC samples. The darker colors of

Table 4. Electrical characteristics of PV cells with the different DLARC thicknesses and single SiN_x ARC

Group	PCE	Fill factor	I_{sc}	V_{oc}	I_{max}	V_{max}	R_s
	(%)	(%)	(A)	(V)	(A)	(V)	(ohm)
A	18.13	78.4	8.93	0.63	8.39	0.53	0.00258
B	18.22	78.4	8.97	0.63	8.42	0.53	0.00254
C	18.24	78.34	8.98	0.63	8.43	0.53	0.00254
D	18.18	78.42	8.96	0.63	8.41	0.53	0.00251
E	18.12	78.42	8.92	0.63	8.38	0.53	0.00248
F	17.71	79.29	8.62	0.63	8.11	0.53	0.00182

DLARC samples with increasing DLARC thickness are illustrated in Figure 5. Thus, SiO_xN_y:SiN_x DLARC can better absorb the high photon energy (blue wavelength) than a single SiN_x ARC sample.

The Electrical Characteristics of the PV Cells

Table 4 shows the electrical characteristic results of PV cells with the different DLARC thicknesses and single SiN_x ARC. It was observed that all samples generate the V_{oc} and V_{max} at 0.63V and 0.53V, respectively. The samples with DLARC layer (sample A-E) provide more power conversion efficiciency (%PCE) than the single SiN_x ARC sample, which relate to lower %WR comparing sample F due to more photon absorbtion ability. It also results in more photocurrent generation with more I_{sc} and I_{max}. Although, the optimal SiO_xN_y:SiN_x ratio thickness of 0.5:0.5 was predited to result in the improvement of %PCE of PV cells in the mass-scale production, the total DLARC thickness is still an important drawback and effects to an increase in the series resistance (R_s) in the cells. Increasing R_s value directly affects a decrease of fill factor (FF) (Green, 1982) and a suppressing PCE% improvement as depited in Figure 6. In this paper, the PV cells with SiO_xN_y:SiN_x DLARC layer show the PCE% improvement around 18.12-18.24%.

The fill factor is the ratio of the actual maximum obtainable power to the product of the open circuit voltage and short circuit current. This is parameter in evaluating performance in solar cell technology. (Blakers *et al*., 2013)

$$FF = FF_0\,(1 - \frac{R_S I_{SC}}{V_{OC}}) \qquad (1)$$

when FF : Fill factor
FF_0 : ideal fill factors
R_S : series resistance ; Ω
I_{SC} : current short circuit ; A
V_{OC} : voltage open-circuit ; V

If Rs is a lot less than this quantity or R_{SH} a lot larger, there will be little effect upon the fill factor. Defining a normalized resistance, R_S/R_{CH}, an approximate expression for the fill factor in the presence of series resistance.

Group C have high efficiency more than other group because high I_{sc}. measurements and graph plots using the company's specialized equipment in the solar cell industry by Solartron Public Company Limited in a lot production condition in the production condition of 100 pieces condition by the terms group A produces 108 pieces, B produces 126 pieces , C produces 152 pieces, D and E produces 135 pieces. the results are shown in Figure 8, with the highest, lowest and middle values of the manufactured workpiece. and Table 5 shows the values from conditions A to F.

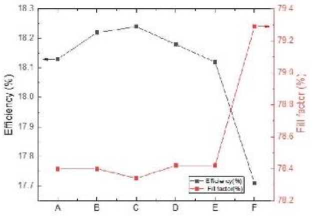


Figure 6. Fill factor and %PCE of PV cells with the different DLARC thicknesses and single SiN_x ARC

Conclusions

SiN_xO_y : SiN_x double layer anti-reflection coating (DLARC) on PV cell can form a black solar cell with gradient index results in an improvement of photocurrent generation. The OPAL-2 simulatio predicts the minimizing optical losses of 3.67% for 0.5:0.5 SiN_xO_y: SiN_x ratio thickness of DLARC layer due to the enhancement of the photogenerated current and low %WR around 2.03 %. PV cells with SiN_xO_y: SiN_x DLARC and SiN_x ARC were fabrication in the mass-scale production under the optimal DLARC ratio thickness of 0.5:0.5 condition. The minimizing reflectance of SiO_xN_y:SiN_x DLARC samples found at 2 wavelengths around 430 nm and 640 nm. However, the increase of total DLARC thickness shows an increase in %WR at

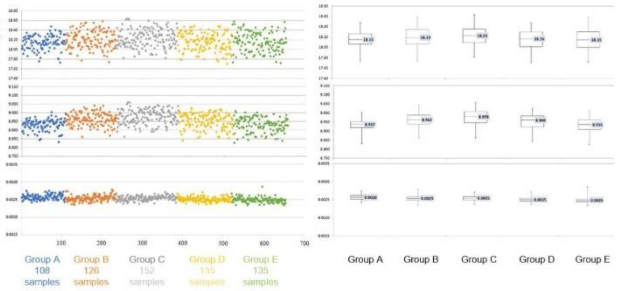


Figure 8. efficiency ,I_{sc} , R_s of PV cells with the different DLARC thicknesses

Table 5. Electrical measurements of PV cells with the different DLARC thicknesses and single SiN_x ARC

Group	Data type	Efficiency (%)	I_{sc} (A)	V_{oc} (V)	Fill Factor (%)	Rs (ohm)
	Max	18.47	9.00	0.636	78.51	0.00269
A	Mean	18.15	8.937	0.630	78.45	0.00262
	Min	17.67	8.843	0.624	78.00	0.00248
	max	18.58	9.04	0.636	78.60	0.00253
B	Mean	18.19	8.96	0.630	78.40	0.00260
	min	17.69	8.85	0.623	77.85	0.00240
	Max	18.63	9.06	0.637	78.57	0.00253
C	Mean	18.23	8.97	0.631	78.35	0.00250
	min	17.82	8.86	0.625	77.74	0.00248
	Max	18.48	9.02	0.634	78.62	0.00253
D	Mean	18.16	8.96	6.629	78.38	0.00250
	Min	17.71	8.84	0.623	78.35	0.00240
	Max	18.58	9.01	0.637	78.81	0.00293
E	Mean	18.15	8.93	0.629	78.43	0.00250
	Min	17.73	8.835	0.624	77.5	0.00248
F	Max	18.11	8.70	0.636	79.66	0.0017

500-800 nm (Orange light region). The dark colors of DLARC samples (black cells) with an increasing DLARC thickness can better absorb higher photon energy (blue wavelength) than a single SiN_x ARC sample. The samples with DLARC layer (black cells) provide the PCE% improvement around 18.12-18.24% compared with the single SiN_x ARC sample with 17.71%P CE. It also results from the more photocurrent generation with more I_{sc} and I_{max}. However, the total DLARC thickness directly effects to an increase in the series resistance (R_s) in the cells resulting in a suppressing PCE% improvement.

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