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ABSTRACT: In order to enhance photon transmission into multicrystalline silicon solar cells, double-layer antireflection coatings (ARC) were simulated using the measured optical constants of hydrogenated silicon oxynitride SiO_xN_y:H and hydrogenated silicon nitride SiN_x:H layers deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD). On polished surfaces, these optimized structures have the potential to increase the short-circuit current by more than 2% for non-encapsulated cells and up to 0.5% for encapsulated cells, in comparison with the standard single SiN_x:H ARC. Industrial multicrystalline silicon solar cells were fabricated in order to validate the simulations. In spite of an inhomogeneous NaOH textured surface, the short-circuit current have shown an increase up to 2.3%, which highlights the potential of such structures for laboratory high-efficiency solar cells.
Keywords: Antireflection Coating, SiON, SiN, Multicrystalline Silicon

1 INTRODUCTION

Minimizing the front reflection of solar cells is one of the strong points to achieve a good efficiency. Hydrogenated silicon nitride layers (SiN) are widely used as antireflection coating (ARC) for silicon solar cells [1-2]. The low temperature deposition process (e.g. PECVD) leads to a non-negligible content of hydrogen within the SiN layer, which consequently provides good passivation properties of defects situated at the silicon surface and within the bulk of multicrystalline silicon (mc-Si) [3,4].

To decrease the surface reflectance, many authors already proposed several solutions, often based on SiN multilayers ARC [5-8]. In our study, we propose to use silicon oxynitride (SiON) in combination with SiN to perform double layer ARC (DARC) and apply it to mc-Si solar cells. The SiON has the advantage of having a refractive index n which can be varied between those of SiO_2 and SiN ($1.46 < n_{SiON} < 1.85$). Moreover, the extinction coefficient k of this dielectric is inferior to 10^{-3} for wavelengths above 300 nm. This makes SiON a good candidate for ARC optimization [9].

To investigate the potential of such DARC, we considered the whole optical index range that can be obtained with our PECVD SiON and SiN layers. Then, simulation was carried out to determine the most promising DARC structure for mc-Si cells with and without encapsulation. Lastly, solar cells were prepared to confirm the improvement predicted by our simulation.

2 SIMULATION

2.1 Methodology

ARC layers take advantage of destructive interference phenomena in order to minimize the reflectance (R) for a central wavelength (like in this work, λ=600 nm is usually chosen as it is near the solar spectrum maximum and allows a good penetration of the photons within the solar cell). In the case of SiN, the absorption (A) within the ARC layer must be taken into account and the transmission coefficient (T=1-R-A) is the preferred parameter to be optimized.

On the one hand, the optimum refractive index and thickness of the different layers were determined using the matrix method for thin-film calculations [10]. A Matlab program was designed including these equations in order to determine the exact "quarter-wavelength" solutions as well as "intermediate" solutions giving non-ideal stacks with low reflection coefficient R. Two cases were considered: solar cells without and with encapsulation. In the first case, the refractive index of the exterior medium was set to n_0=1 (Air). For encapsulated solar cells, the glass plate and the EVA film (Ethylene-Vinyl Acetate, used as adhesive between the glass plate and the cells) were considered as a unique exterior medium with n_0=1.46. Furthermore, the reflection at the glass plate surface of the solar panel was not taken into account, as it is optically independent of interference phenomena occurring within the ARC layer.

On the other hand, a large set of SiON and SiN single layers was deposited on Si wafers in a direct low frequency (440 kHz) PECVD reactor, providing the complete range of SiON and SiN stoichiometries [2, 8]. The films were deposited at 370°C using SiH_4, NH_3 and N_2O as precursor gases. The thickness, wavelength-dependant refractive index n(λ) and extinction coefficient k(λ) of the different thin films were deduced by spectroscopic ellipsometry (JobinYvon UVISEL – 248 nm<λ<827 nm), using Tauc-Lorenz dispersion model [11] (in the following, all refractive indexes are given for λ=605 nm). The obtained data library of optical indexes (n, k) was introduced in the multilayer optical simulator IMD (Bell Labs [12]) in order to compute the wavelength-dependant reflection, absorption and transmission coefficients through the desired SiON/SiN stack layers (encapsulated or not). Reflectivity measurements operating with a Labsphere integrating sphere were carried out and the results were compared to the computed reflectance in order to validate the simulation. To investigate the impact of the stack absorption, the transmission coefficient obtained with IMD was introduced in PC1D solar cell simulator [13] as (1-T) for the "front external reflectance". Thus, we directly obtained the improvement in short-circuit current density J_{cc} for the DARC compared to the standard single ARC. The PC1D parameters are given in Table I. They are typical of industrial mc-Si solar cells.

Table I: PC1D parameters

Silicon	
Thickness	220 µm
Base P doping	1.10^{16} cm^{-3}
Diffusion length	140 µm
Emitter N doping	3.10^{20} cm^{-3}
Rear surface reflectivity	70 %
SRV on front side	5000 $cm.s^{-1}$
SRV on back side	1000 $cm.s^{-1}$

2.2 Non-encapsulated solar cells results

Table II presents the computed refractive indexes and thicknesses of the layers that form the best stacks. It also displays the corresponding effective reflectivity R_{eff} (obtained with the optical simulations), in addition to the resultant short-circuit current density (simulated with PC1D). These values have to be compared with the case of a single ARC (Ref.).

Table II: Refractive indexes (n_i), thicknesses (e_i), effective reflectivity (R_{eff}) and short-circuit current (J_{cc}) results obtained from the simulation of non-encapsulated cells (i=1 stands for the top layer and i=2 for the bottom layer).

	n_1(e_1 nm)	n_2(e_2 nm)	R_{eff} (%)	J_{cc} ($mA.cm^{-2}$)
Ref	2.03 (73)	-	10.2	33.48
A21	1.58 (95)	2.50 (60)	**4.2**	33.56
A22	1.58 (95)	3.14 (48)	4.9	31.88
A24	1.46 (102)	2.08 (62)	6.5	**34.14**
A25	1.46 (55)	2.10 (50)	6.9	**34.18**
A26	1.55 (50)	2.16 (47)	7.0	**34.16**

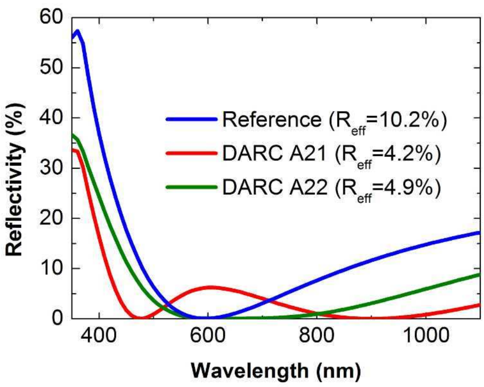

Figure I: Computed reflectance versus wavelength for the A21 "W" profile and the A22 "U" profile. The corresponding effective reflectivity R_{eff} of the stacks is also indicated. The reference is a standard SiN single layer.

The reflectance values strongly decrease thanks to the DARC structure. For the three exact "quarter-wavelength" solutions, two different reflectivity profiles were found: "U" profiles like A22 which exhibit a reflectance equal to zero for the central wavelength and "W" profiles like A21 with two reflectance minima (Figure I – the third solution A23 was discarded as it involves refractive index out of the range of the data library). Both profiles give nearly similar effective reflectivity, but affect different spectral regions. However, if the effective reflectivity is strongly reduced compared to the single layer ARC, the short circuit current is not significantly changed (Table II). This highlights the strong absorption of short-wavelength photons ocurring within the high silicon content SiN layers, which reduces the photon transmission into the cell.

The results using "intermediate" stacks with lower SiN refractive indexes show an improvement of up to 0.7 $mA.cm^{-2}$ (A24-A26 - Table II), despite "higher" effective reflectivities. With its "W" profile, the A24 DARC seems to be a good candidate for solar cells with good bulk and rear side passivation schemes, as well as for back-contacted solar cells, as it allows a better transmission of the infrared part of the solar spectrum (Figure II). The two other solutions A25 and A26, with a "U" profile, involve thinner layers than A24. This can be an advantage looking at the ARC deposition velocity and in order to avoid contacting problems during the firing of the solar cell contacts through the ARC. For these stacks, the improvement of the current density is mostly due to a higher transmission of high energy photons compared to the single ARC. Thus, the improvement should be stronger for solar cells with low-doped or selective emitter. The computed external quantum efficiency (EQE) highlights the impact of the absorption within the stacks, comparing it with the corresponding reflectance (Figure II).

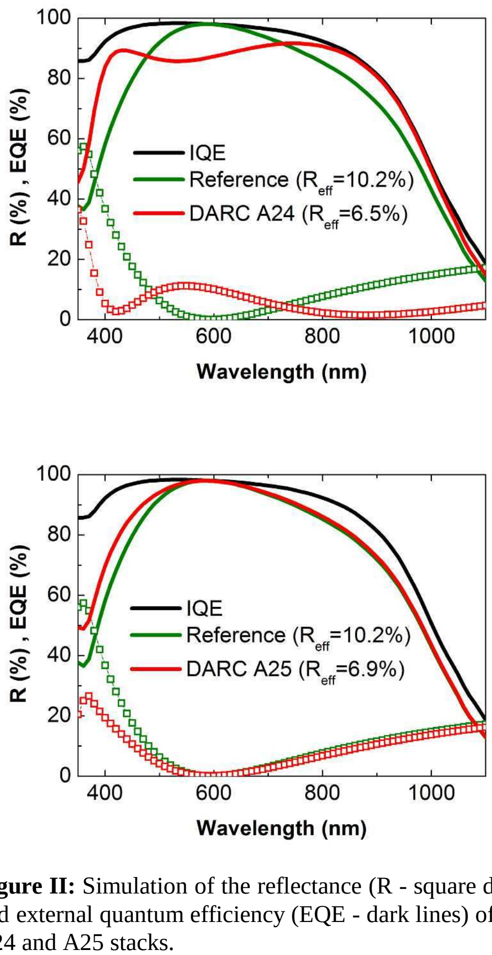

Figure II: Simulation of the reflectance (R - square dots) and external quantum efficiency (EQE - dark lines) of the A24 and A25 stacks.

2.3 Encapsulated solar cell results

The same simulations were performed for encapsulated cells (i.e. with an outside refractive index set to 1.46). The best parameter combinations obtained are detailed in Table III. Note that for the single layer case (Ref.), the refractive index is not the “quarter-wavelength” solution as it would correspond to a strong absorption coefficient. Indeed, it has been determined to maximize transmission through the SiN layer, as described for the DARC case. It can be added as well that all the stack combinations of 3 or more layers involve high absorption SiN films, which prevent their application to Si solar cells.

Table III: Refractive indexes (n_i), thicknesses (e_i), effective reflectivity (R_{eff}) and short-circuit current (J_{cc}) results obtained from the simulation of encapsulated cells (i=1 stands for the top layer and i=2 for the bottom layer).

	n_1(e_1 nm)	n_2(e_2 nm)	R_{eff} (%)	J_{cc} (mA.cm^{-2})
Ref	2.16 (68)	-	6.5	34.40
E21	2.03 (74)	2.83 (53)	2.2	33.30
E23	1.71 (88)	2.83 (53)	2.7	33.24
E24	2.03 (50)	2.83 (35)	**2.0**	33.89
E25	1.61 (60)	2.36 (56)	3.6	34.38
E26	1.61 (69)	2.24 (61)	4.6	**34.56**

All these stacks involve relatively high refractive index layers, and only one scheme shows better results than the standard ARC. The corresponding increase in short-circuit current is much lower than for the case of non-encapsulated cells (0.5% against 2%). Thus, this improvement seems to be insufficient to be incorporated into the solar cell process because it would imply an additional SiON deposition step as well as new firing and silver paste optimizations.

2.4 Conclusion

For ARC and DARC applications, the parameter to be optimized is the transmittance through the stacks in order to take into account the absorption within the layers and thus obtain the higher short-circuit current as possible.

With the best DARC obtained, the simulations show that we can expect a non-negligible 2% relative increase of the short-circuit current for non-encapsulated solar cells. On the other hand, photon transmission into encapsulated solar cells cannot be significantly improved with such DARC structures.

3 APPLICATIONS TO MULTICRYSTALLINE SOLAR CELLS

In order to validate the simulations in the case of a non-encapsulated cell, we manufactured 3 sets of 8 125×125 mm^2 mc-Si solar cells, NaOH textured, with different ARC schemes. The mc-Si substrate thickness and doping are similar to the ones used for simulation (see Table I).

The cells were chemically textured in a NaOH solution. This anisotropic solution gives rise to a non-homogeneous texturization which depends on the grain orientation. Consequently, the thickness of the deposited dielectric layers differs according to the mc-Si grain (the deposition velocity is lower on texturized grains than on polished ones). Thus, the reflectivity optimization was made for non-texturized grains.

Three types of ARC were tested: a single SiN ARC layer (reference); a DARC defined by the simulated stack A24; a DARC defined by the simulated stack A25 (see Table II). The cells were made in an industrial process line at Photowatt except for the ARC deposition, carried out at the INL in a direct PECVD reactor working at 440 kHz.

3.1 Reflectivity

The reflectivity profiles are in agreement with the simulation (Figure III – the measurements were performed before the front contact deposition). The slight difference between the simulation and the experimental data are attributed to the texturized grains which may affect the deposited layers thicknesses and thus the global reflectivity.

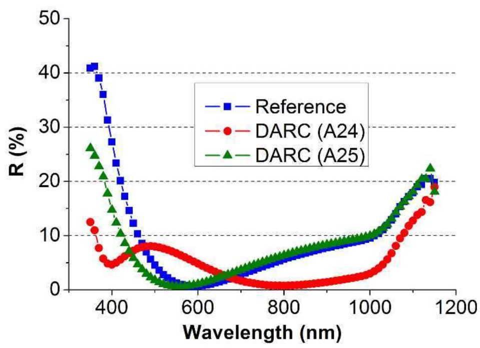

Figure III: Measured average reflectance of the 3 sets of industrial solar cell.

3.2 Solar cells results

Table IV shows the results of the current-voltage characterization of the mc-Si solar cells. An increase in short-circuit current up to 2.3 % is obtained for the A24 DARC in comparison with the single ARC, which is in accordance with the simulation. This induces a 1.7 % relative increase of the efficiency and shows the good potential of such DARC structure. This potential is thought to be even higher for high efficiency solar cells with a good Back Surface Field, as the transmission of low energy photons is greatly enhanced (Figure III).

Table IV: Current-voltage characterization results. All the gains are relatives.

	V_{oc} (mV)	I_{cc} (mA.cm^{-2})	FF (%)	Efficiency (%)
Ref	599	32.99	77.1	15.13
A24	600	**33.94**	76.6	**15.39**
Gain	*+0.2%*	*+2.3 %*	*-0.6%*	*+1.7%*
A25	598	**33.13**	76.9	15.13
Gain	*-0.2%*	*+0.5%*	*-0.2%*	*+0.0%*

The short-circuit current increase for the A25 DARC is moderate compared to the simulation. In this case, the gain in reflectivity affects only the short wavelength photons which are absorbed in the first micrometers of the cell where the emitter stands (Figure III). Hence, the moderate increase in current can be explained by higher emitter recombination in the industrial solar cells than in the “theoretical” solar cell used for the simulation.

For both DARC, the open-circuit voltage remains similar to the reference cells, which indicates that the DARC stack is as efficient as the single ARC layer for surface passivation. The slight decrease of the fill factor may be attributed to the use of the same firing process for the front contact formation as the reference. Optimization might be needed for the firing step profile in order to obtain good contact formation through the thick DARC stack.

For such an efficiency improvement, and for laboratory purpose, the modification of the fabrication process is minor because both SiON and SiN layers can be deposited during the same PECVD step. Moreover, the gain in efficiency should be higher using an optimized firing step for the DARC.

4 CONCLUSION

In order to increase the mc-Si solar cell performance, we investigated the potential of a double antireflection layer on the front side of the solar cells. PECVD silicon oxynitride was used to complete the refractive index range between silicon nitride and silicon dioxide.

The simulations showed that we have to choose carefully the SiN layer due to its high absorption coefficient when its refractive index is high. Due to this absorption, none of the layer combinations gave significant improvement of the short-circuit current in the case of encapsulated solar cells. However, two DARC profiles showed a potential increase of 2% of the short-circuit current in the case of non-encapsulated solar cells. The industrial mc-Si solar cells results confirmed a gain in efficiency by using such a SiON/SiN stack as a DARC, which thus has a good potential for laboratory high efficiency Si solar cells.

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