BLACK MULTICRYSTALLINE SOLAR MODULES USING NOVEL MULTILAYER ANTIREFLECTION STACKS

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ABSTRACT: Today multi- and monocrystaline solar cells are typically wet-chemically textured and coated with a thin layer of silicon nitride to reduce losses due to light reflection and for electrical passivation of the silicon surface. In this paper we investigate a layer stack consisting of silicon nitride (SiNx:H) with a high refractive index at the silicon interface, an intermediate SiNx:H layer and on top a silicon oxynitride layer with a low refractive index. This SiNx/SiOxNy-multilayer approach significantly reduces reflection in the range between 350 – 1200 nm both on cell and module level. Electrical parameters of mc-Si solar cells and encapsulation losses are presented showing that the SiNx/SiOxNy-stack can improve cell efficiency by 0.24 % (abs.) and module efficiency by 0.08 % (abs.) compared to a SiNx-single layer coating. The stack was designed to give a uniform black color after encapsulation under solar glass and filler sheet. Special care was taken to ensure that the appearance of the encapsulated cell depends little on the total thickness of the stack. An optical model is presented that predicts the short circuit current on a textured mc-Si solar cell with multilayer antireflection coating.
Keywords: Silicon-Nitride, Silicon-Oxynitride, Antireflection Coating

1 INTRODUCTION

Incoupling and absorption of light in the active layer of a solar cell is one of the major processes of power conversion. Two dominating techniques to suppress reflection on a Si-wafer are well-established. First the texturing of the silicon surface [1], [2] with the aim to increase multiple reflection at the surface and to shift the generation of free carriers closer to the pn-junction by oblique coupling of incident light [2]. Second the coating with antireflection layers (ARC) with the aim to reduce the reflectance at the surface. Another crucial impact of the latter is the electrical surface passivation [3]–[7]. Some results on improved antireflection coatings using multiple layers are already published [8] - [11], but up to now no deciding impact on solar cell mass production was shown. Present technology typically employs a single layer antireflection coating of silicon nitride with a refractive index n of about 2.05 and a thickness d of approximately 75 nm which suppresses the reflection at a wavelength $\lambda_{Rmin} = 4{\cdot}n{\cdot}d = 615$ nm. This standard procedure has the following disadvantages:

- Reflection losses still amount to 2.12 $mAcm^{-2}$ on cell level and 2.06 $mAcm^{-2}$ after encapsulation considering a typical internal quantum efficiency.

- The color of the solar cell depends heavily on the thickness of its ARC-layer. With standard process deviations of PECVD coating equipment the color ranges from dark purple to light blue. The non-black appearance of wafer based silicon solar cell modules is a disadvantage compared to black thin film modules.

The purpose of this work is to introduce a layer stack of silicon nitride and silicon oxynitride overcoming the disadvantages of single layer coatings. The development of a SiNx/SiOxNy-stack was supported by a mathematical description of a multilayer coated textured surface within an encapsulation. The model calculates the absorption and reflection as a function of optical constants and layer thicknesses by the transfer matrix method [14]–[20]. Based on this model we developed a multi layer ARC system on standard manufacturing machines optimized for typical industrial encapsulation materials leading to an absolute efficiency increase of 0.08 %. The modest efficiency increase despite the significant reflection loss is due to the fact, that there are only few dielectric films available which are transparent, passivate both the surface and the volume of silicon solar cells and have a refractive index between silicon (n = 3.4) and solar glass (n = 1.47) and filler sheet (n ≈ 1.5) respectively. Although the refractive index of SiNx:H can be easily tuned from silicon rich SiNx:H films (n > 3) to nearly stoichiometric SiNx:H films by changing the gas ratio of the precursors SiH_4 and NH_3, the increasing absorption of the film for n > 2.05 soon overcompensates the lower reflection for SiNx single layers. Stoichiometric Si_3N_4 films have a refractive index of around n = 1.9. As a second dielectric film SiOxNy was introduced with a tunable refractive index ranging from n = 1.47 (SiOx) to n = 1.9 (SiNx). Thus by using both materials in layer stacks, one can vary the refractive index from 1.47 < n < 3 with the constraint that silicon rich SiNx:H-layers must not be too thick to lower the overall absorption of the layer stack. In Fig. 1 a schematic picture of the SiNx/SiOxNy layer stack investigated in this study is shown.

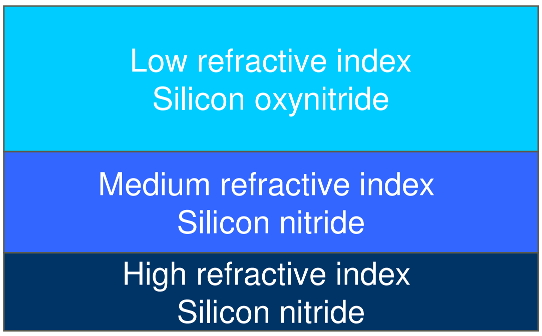

Figure 1: Scheme of SiNx/SiOxNy layer stack. The SiNx-layers were deposited using silane and ammonia as precursor gases with different gas ratios, the SiOxNy layer with silane, nitrous oxide and ammonia.

2 EXPERIMENTAL

2.1 Deposition of ARC layer stack

SiNx:H and SiOxNy:H layers were deposited using a parallel plate reactor with a capacitive plasma discharge. Excitation frequency was 40 kHz. The refractive indexes of the dielectric layers were adjusted by changing the gas flow of the precursor gases silane (SiH_4), ammonia (NH_3) and nitrous oxide (N_2O). The deposition gas pressure in the chamber was 1.5 Torr and the RF-power was 6680 W.

2.2 Cell preparation

Multicrystalline solar cells were prepared from p-type silicon wafers (1 Ωcm) using a standard industry manufacturing process. After acidic texturization and phosphorous diffusion, the wafers were coated with the SiNx/SiOxNy layer stack and metalized by screen printing.

2.3 Analysis

Optical reflectance was measured with a spectrometer on a textured surface using an integrating sphere. The optical constants (n,k) of the SiNx:H and SiOxNy:H layers were determined by spectroscopic ellipsometry at three angles (55 °, 65 ° and 75 °). The SiNx:H and SiOxNy:H layers were deposited on polished Si-substrates with <100> orientation (250 µm thickness, 1-2 Ωcm resistivity).

3 OPTICAL MODELLING

3.1 Modelling multilayer stacks

The optical behavior of films with layer thickness in the order of or below the coherence length of sun light [12] differs strongly from optical thick films or bulk like materials. For the latter light absorption can be described by series expansions of Lambert-Beers law [13]. In contrast systems of thin films need the consideration of interference effects of the electro magnetic waves due to multiple reflections within the layer stack [13, 14]. The Maxwell equations and the resulting Fresnel equations are the cornerstone for the mathematical description of such systems. A very elegant way to calculate the optical behavior of a multi layer stack of thin isotropic films is the transfer-matrix-method (TMM) [14-20].

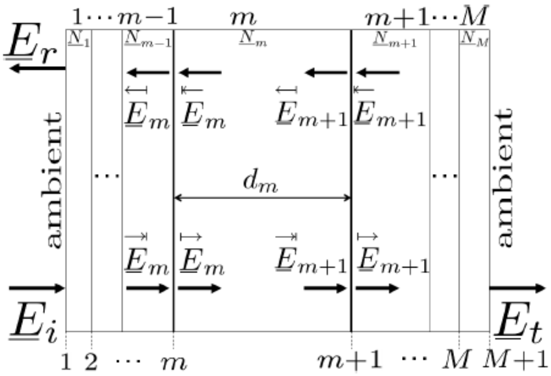

Figure 2: Schematic of electric field amplitudes in a M layered stack with M + 1 interfaces illuminated from the m=1 side.

A stack of M layers and M+1 interfaces which is illuminated from the m=1 side (see Fig. 1) can be written as the matrix product:

$$\begin{pmatrix} \underline{E}_i \\ \underline{E}_r \end{pmatrix} = \prod_{m=1}^{M} (I_m L_m) I_{M+1} \begin{pmatrix} \underline{E}_t \\ 0 \end{pmatrix} = P \begin{pmatrix} \underline{E}_t \\ 0 \end{pmatrix} \quad (1)$$

with I_m the interface matrix of interface m, L_m the layer matrix of layer m and their total product P the system transfer matrix. I_m is a function of the wavelength dependent complex optical constants (OC) of both interface media and also depends on the angel of incidence at the interface m. L_m depends on the OC of layer m and the angle of the light propagation within that layer.

Reorganizing (1) leads to the complex electric field amplitudes of the reflected (r) and transmitted (t) waves for a given incident (i) electric field amplitude as a function of the matrix elements of P. The corresponding light intensities can be calculated by [14-20]:

$$R = \left(\frac{\underline{E}_r}{\underline{E}_i} \right)^2$$

$$T = \frac{n_t \cos \phi_t}{n_i \cos \phi_i} \left(\frac{\underline{E}_t}{\underline{E}_i} \right)^2 \quad (2)$$

With the boundary conditions given by the results of (1) and Poyntings theorem [21] the absorption A_m within each single layer of the stack can be expressed [18].

Layers with thicknesses above the coherence length of sun light (approximately 600nm [12]) need additional consideration, as interference structures are smoothed or vanish completely. Several methods to implement such layers in the TMM exist in literature [17-20]. We chose the method of averaging several solutions of the total stack with several variable phase shifts of the electro magnetic wave within the thick layers [19].

The optical model for the representation of an encapsulated silicon solar cell consists of a glass (3 mm), an EVA (0.5 mm), the anti reflection multi layer stack, a layer stack representing the emitter and a semi infinite silicon substrate. All OC where obtained using spectroscopic ellipsometry on polished reference samples.

3.2 Calculation of the short circuit current

For the evaluation of the short circuit current density of the stack, the sum of absorption within the emitter layers and the transmitted light into the silicon was taken into account:

$$I_{SC} = \int_{350nm}^{1200nm} j_{phot} * IQE * (1 - R_G) * (1 - A_G) * (1 - F_{Met}) d\lambda \quad (3)$$

with I_{SC} the short circuit current, j_{phot} the photon current density of AM1.5g, IQE the internal quantum efficient, R_G/A_G the reflection/absorption of the layer stack and the solar glass/filler sheet and F_{Met} the area fraction of the cell that is shaded by the screen printed contact.

The texturization of the silicon surface was taken into account by using a simplified model of the acidic texture. It is assumed that the acidic etch is isotropic from a point-shaped origin (Fig 3). That means a fraction of the incident light is reflected one time with an angle distribution α(x) and some of them two or more times with different angles of incidence α(x), β(x).

Further details will be published elsewhere.

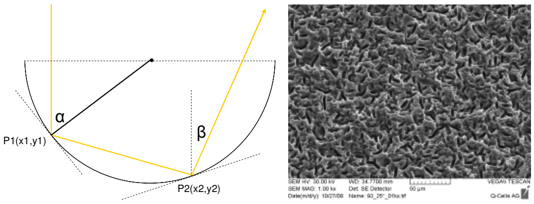

Figure 3: (left) Scheme of an acidic texture with a ray of light being reflected two times with an angle α and β; (right) REM picture of an acidic textured mc-Si wafer

4 RESULTS AND DISCUSSION

4.1 Reflection and absorption of SiNx/SiOxNy-stacks

Fig. 4 shows the simulated and measured reflectance of a SiNx/SiOxNy layer stack compared to a SiNx-single layer. The backside reflection at a wavelength $\lambda > 950$ nm was not included into the model. Between 350 and 950 nm the model predicts very well the measured reflectance of the textured wafer. The reflection minimum, which is between 0.6 – 0.8 % for a SiNx single layer with a refractive index of n = 2.05 depending on the texture, can be precisely reproduced assuming different angles of incidence.

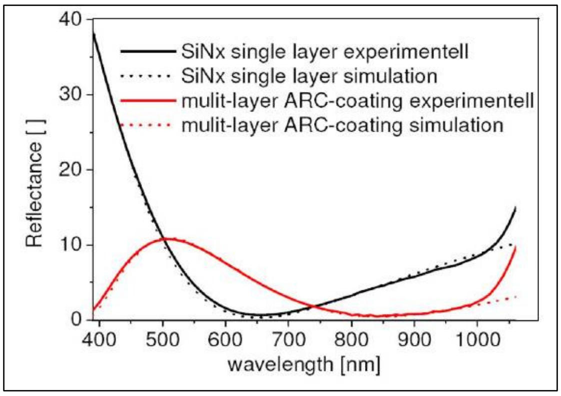

Figure 4: Simulated and measured reflectance of a SiNx-single layer and SiNx/SiOxNy multilayer on acidic textured mc-Si wafers.

The average reflectance between 350 nm and 1200 nm is reduced from 11.5 % to 5.9 % demonstrating the potential of multilayer antireflection coating on cell level. In the blue region for $\lambda < 500$ nm part of the reduced reflection is compensated by an enhanced absorption of the SiNx layer with a high refractive index. After encapsulation of the solar cell, the advantage of the SiNx/SiOxNy multilayer is reduced significantly, mainly because the solar glass with n = 1.47 is a new optical interface (4 % of the incident light is already reflected at the interface to air) and due to additional internal total reflection of reflected light at the filler/glas and glas/air interface under oblique angles due to the surface texture of the solar cell and metal contacts. The average reflection after encapsulation is only reduced from 8.2 to 7.1 %.

4.2 Color of encapsulated solar cells

Fig. 5 shows encapsulated mc-Si solar cells with a single layer SiNx-coating (blue) and a SiNx/SiOxNy layer stack (black). Whereas on the blue module, one can still see grain boundaries and dislocations on the multicrystalline cell, the black module gives a very homogeneous appearance making it undistinguishable from full square monocrystalline cells.

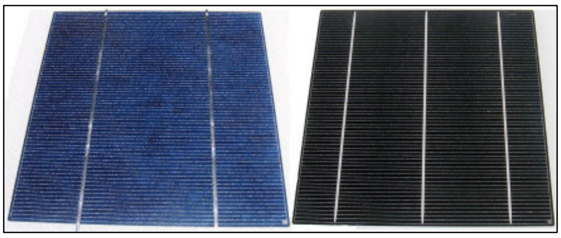

Figure 5: Encapsulated mc-Si wafers with a SiNx-single layer (left) and a SiNx/SiOxNy multilayer stack (right).

The SiNx/SiOxNy stack was especially designed to give the same color of the encapsulated solar cell even when the total layer thickness changes. This is important since thickness deviation due to different wafer texturization and inhomogeneous deposition of the antireflection coating is a serious quality issue. In Fig. 6 a module is shown where the total layer thickness of the SiNx/SiOxNy stack was varied on purpose and one can see almost no change in the optical appearance although the total thickness variation is more than 30 nm.

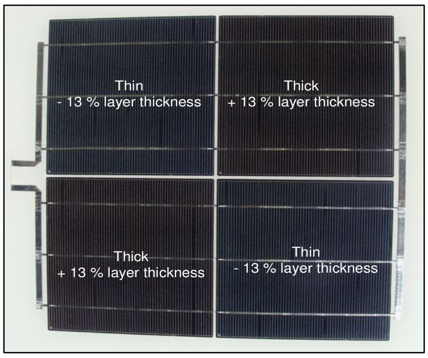

Figure 6: Four encapsulated mc-Si solar cells. The upper left und the lower right were coated too thin (-13 % rel. of the desired film thickness), the lower left und upper right too thick (+ 13 % rel. film thickness). The picture was taken outside on a sunny day.

4.3 Electrical parameters of solar cells

The novel SiNx/SiOxNy stacks were tested on acidic textured mc-Si cells (156*156 mm) and compared to standard single layer SiNx-coatings. As shown in table I, the efficiency of the SiNx/SiOxNy-stacks is 0.24 % higher due to an increased short circuit current of 0.47 $mAcm^{-2}$ and a better open circuit potential of 2.2 mV. The mismatch factor which corrects the different spectral output of the solar simulator and the AM1.5g spectrum was matched to account for the different reflection of the SiNx/SiOxNy stack.

	η [%]	Isc [$mAcm^{-2}$]	Voc [mV]	FF [%]
SiNx/SiOxNy multi layer	16.53	34.09	620.1	78.21
SiNx-single layer	16.29	33.62	617.9	78.40

Table I: Median cell parameters of 100 neighbored cells. The measurement of the short circuit current is mismatch corrected accounting for the different reflection of the SiNx single layer and the SiNx/SiOxNy multilayer

The higher open circuit potential reflects the better passivation of the Si/SiNx interface. Fig. 7 shows the improved internal quantum efficiency (IQE) of SiNx/SiOxNy coated solar cells for $\lambda < 450$ nm (emitter region) whereas the IQE for $\lambda > 800$ nm (silicon bulk) remains unchanged.

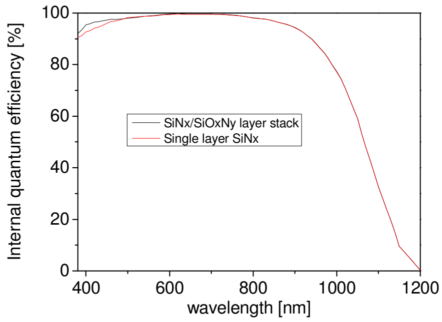

Figure 7: Internal quantum efficiency (IQE) of a SiNx-single layer and a SiNx/SiOxNy multilayer. Each curve represents an average IQE of six neighbored mc-Si solar cells.

After encapsulation the short circuit current of an acidic textured solar cell typically increases significantly despite additional shading of the strings and absorption of the filler sheet and solar glass. First, multiple reflections within the solar glass enhance the collection of photons that were reflected on the metallization. Second, the introduction of an additional optical layer with a refractive index between air and silicon reduces the overall reflection. In table II it is shown that after encapsulation the Isc increase is 0.38 $mAcm^{-2}$ less for the SiNx/SiOxNy layer stack. That means the overall Isc gain decreases from 0.47 $mAcm^{-2}$ on cell level to 0.09 $mAcm^{-2}$ after encapsulation (overall efficiency increase: 0.08 %). Since the index of refraction of glass (n = 1.47) is relatively close to that of the SiOxNy the benefit of the SiNx/SiOxNy layer stack is higher if the incident medium is air.

	Δ Isc encapsulation [$mAcm^{-2}$]
SiNx/SiOxNy multi layer	+ 0.19
SiNx-single layer	+ 0.57

Table II: Isc-gain of SiNx-single and SiNx/SiOxNy multilayer after encapsulation. The cell was stringed before the measurement to have the same shading before/after encapsulation.

5 CONCLUSION

A SiNx/SiOxNy multi layer stack as an ARC is introduced and compared to a single layer SiNx coating.

- The efficiency increase on acidic textured mc-Si solar cells is 0.24 % and 0.08 % after encapsulation. The increased performance is due to less reflection and a better passivation.
- After encapsulation the SiNx/SiOxNy layer stack is black. The color of the module is very insensitive to the total layer thickness of the stack.
- An optical model based on the TMM can simulate the absorption and reflection of multilayer stacks for different angles of incidence. It can predict the reflection of antireflection layer stacks on flat and textured surfaces with/without encapsulation and thus predict short circuit current of the solar cell.

6 ACKNOWLEDGEMENT

The work is supported by the EFRE fund of the EU and Sachsen-Anhalt (Project Optifront – 6003399501).

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