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# Electrical characterization of passivation layers for p-type multi crystalline silicon EWT solar cells by numerical simulation

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***Abstract***
*In this study, the dielectric effects on solar cell efficiency were investigated. Different materials, such as $Al_2O_3$, $HfO_2$, $TiO_2$ and $SiO_2$, were deposited by various techniques on the front side of a p-type EWT (Emitter Wrap Through) multi crystalline silicon (mc-Si) solar cell. The passivated layer thickness was optimized using the software Matlab. The recombination velocities utilized in the simulation were taken from the literature. Using the software TCAD (2D) Silvaco/Atlas, the best results (for electrical parameters) were achieved with $TiO_2$ (refractive index n = 2.6 at λ= 620 nm) for a thickness of 5 nm; a solar cell efficiency around 20.5% was obtained*

*Keywords: p-type EWT mc-Si solar cell; passivation layers; reflectivity;, absorption; efficiency; simulation; Silvaco/Atlas.*

## 1. Introduction

The energy conversion efficiency of a solar cell is limited by two factors: theoretical (which cannot be avoided) and technological (which can be improved). The technological factors are of three forms: optical, electrical (recombination) and resistive. The present work is part of a logic to increase the conversion efficiency of multi crystalline silicon solar cells by limiting the losses quoted above. Some of these limitations are:

-the shading rate that takes into account the partial coverage of the front surface of the cell by an opaque portion corresponding to the surface of the metal contacts

-the recombination of carriers in the volume and on the cell surface. The EWT (Emitter Wrap Through) structure was proposed for the first time by J.GEE [1] in which the shade rate is equal to zero (PV cells with rear contacts).

Today, and thanks to the excellent quality of the available silicon substrates, photovoltaic solar cells are limited by their surfaces (front and rear), knowing that with the progress of the crystallization techniques, recombination in the volume of the base is not a limiting factor anymore for the cell efficiency. A practical and proven means to improve the solar cell efficiency is through surface passivation. This consists in increasing the collection of the photogenerated carriers by improving their lifetime (or their diffusion length). This is possible, if the recombining action of the defects present on the surface is reduced (reduction of the recombination velocity on front and rear sides of the cell).

For that, thin layers of materials are deposited on the front and/or back sides of the cell to reduce the defects present on the silicon surface.

In addition to their passivation properties, thin films must have adequate optical properties, i.e. they must be non-absorbing and anti-reflective if deposited on the front; and on the other hand, they must have a high internal reflection rate on the rear face in order to limit the losses due to transmission. This work aims to show the effect of the passivation layer thickness deposited on the front side of a p-type EWT silicon solar cell, under Silvaco Atlas-2D TCAD, by using several oxides, like $Al_2O_3$, $HfO_2$, $SiO_2$ and $TiO_2$.

## 2. EWT cell simulation

"In the present work, all the simulations were carried out with (10×10) cm² EWT solar cells, under AM1.5G illumination, and were performed with the software TCAD (2D) Silvaco/Atlas.

EWT solar cells are developed using a p-type multi crystalline silicon substrate with a thickness of 200 µm. The front surface is covered with a SiNx :H antireflective coating to reduce light reflections. A

$n^+p$ junction is created by diffusing a shallow (0.5 µm) n+ layer in the p-type silicon substrate. This diffusion is performed on the front face of the cell and into the holes within the substrate. It should be noted that these holes are made by means of a laser. The back surface field (BSF) is to create a potential barrier at the back of the cell to ensure the reflection of minority carriers. The metallic contacts are screen-printed on the back side of the structure. Aluminum and silver are used for p+ and n+ regions, respectively". [14].

The figure below illustrates the cross-section view of the investigated p-type EWT multi crystalline silicon solar cell.

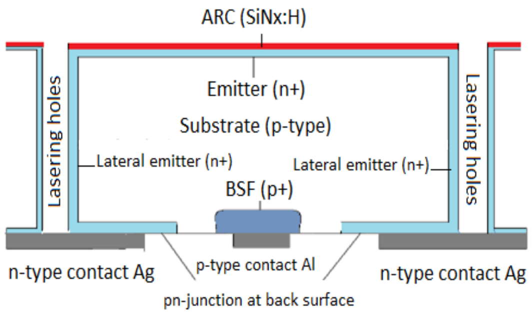


Figure 1: Schematic structure of p-type EWT mc-Si solar cell used during simulation

| | |
|---|---|
| Base | Width = 200 µm<br>Doping = 9E17 cm-3 |
| Emitter | Junction depth =0.5 µm<br>Doping = 1E20 cm-3<br>ERFC (complementary error function) |
| BSF (Back Surface Field) | Width = 5 µm<br>Doping = 5E18 cm-3<br>Gaussian profile |
| Anti-reflective coating $S_iN_x$ :H | Thickness = 80 nm<br>Refractive index = 2.05<br>(at λ = 0.632 µm) |
| Screen printed contacts | Thickness =10 µm<br>Workfunction :<br>W(Ag) =4.08<br>W(Al) = 5.2 |

Table 1: Parameters of the p-type EWT silicon solar cell used in simulation, without passivation layer.

With this parameters, simulation of the p-type EWT multi crystalline silicon solar cell under TCAD (2D) Silvaco/Atlas, gives the results reported in the table below:

| Losses (%) by | | $I_{cc}$ (mA/cm$^2$) | $V_{oc}$ (V) | η (%) |
|---|---|---|---|---|
| reflection | absorption | | | |
| 10.32 | 0.59 | 32.32 | 0.68 | 18.51 |

Table 2: Optical losses and electrical parameters of the simulated cell, without passivation layer (reference cell).

### 3. Program chart

In this paper, the simulation was used to determine the surface passivation effect (using several dielectrics) on the optical and electrical parameters of EWT cells.

We constructed simulation codes to evaluate optical losses (reflection, transmission and absorption) under the Matlab software. Indeed, the optical properties which govern the light propagation in a material are essentially its refractive index n and its absorption coefficient. It is necessary to seek the best configuration which allows having the minimum of reflection and the maximum of transmission according to the thickness d of the different layers.

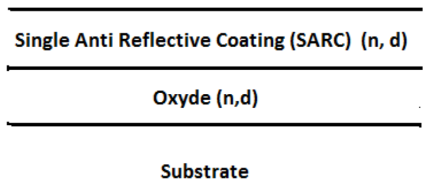


Figure2 : Parameters involved in the simulation under Matlab

Then, we injected the results into a Silvaco / Atlas program to determine the electrical parameters of the cell, namely: short circuit current, open-circuit voltage and efficiency. The procedure is as follows: after a judicious mesh of the device (the mesh must be done with the utmost attention to guarantee the reliability of the results), the structure is describe (the different regions, the electrodes and the doping) and the materials and models used are cited (contacts, materials, interfaces, models ...).

### 4. Passivation of p-type front side EWT cell

The surface recombination velocity has a significant effect on the change in the short-circuit current and the open circuit voltage. Surface recombination at the front can be reduced by decreasing the dangling bonds of silicon, using a passivation layer. These dangling bonds can be neutralized, using oxides such as $Al_2O_3$, $HfO_2$, $SiO_2$ and $TiO_2$. Due to the presence of oxide, they constitute good passivation layers for p-type silicon solar cells. This neutralization operation allows decreasing the surface recombination rate and increasing the minority carrier lifetime. The optical properties of the films, deposited by plasma-assisted atomic layer deposition (ALD), are given in the table below.

| Dielectric layer | Average refractive index (at 620 nm) | Band gap (eV) |
|---|---|---|
| $Al_2O_3$ | 1.65 | 8.8 |
| $HfO_2$ | 2.10 | 5.6 |
| $SiO_2$ | 1.47 | 9 |
| $TiO_2$ | 2.60 | 3.1 |

Table 3: Optical properties of the thin films (dielectrics deposited by plasma-assisted ALD) used in the simulation [3].

By applying a thin coating, a few nanometers thick, the physical characteristics of the substrate are modified. Thin film deposition is a process that must be applied in a controlled manner. The deposition techniques used depend on the way the thin film is to be "created".

Different deposition methods exist and some of these are: the Atomic Layer Deposition (ALD) [3,4,5], Plasma Enhanced Chemical Vapor Deposition (PECVD) [5,6], Thermal Atomic Layer Deposition (T-ALD) [5] and Plasma Enhanced Atomic Layer Deposition (PE-ALD) [5].

| Dielectic layer | thickness | Deposit technique | $\tau_{eff}$ (µs) at $\Delta n=5.10^{15}$ | $S_{eff}$ (cm/s) | $S_{eff}$ (cm/s) reported by literature |
|---|---|---|---|---|---|
| $SiO_2$ [5] | 20nm | T-ALD | 324 | 31 | 10 - 70 |
| $SiO_2$ [5] | 20nm | PECVD | 36 | 277 | 80-400 |
| $Al_2O_3$ [5] | 15nm | T-ALD | 613 | 17 | 5 - 30 |
| $Al_2O_3$ [5] | 15nm | PE-ALD | 3790 | 3 | 2 - 20 |
| $HfO_2$ [7] | 10nm | ALD | 650 | 55 | / |
| $TiO_2$ [13] | 10nm | ALD | 730 | 20 | / |

Table 4: $\tau_{eff}$ and $S_{eff}$ values (kept from literature) used in the simulation for different dielectric materials

## 5. Results and discussion

To optimize the solar cell efficiency, we started by adjusting the single anti-reflective coating (SARC) thickness to the dielectric thickness. For that, a numerical simulation Matlab code (developed in our research team [8]) was used; the transfer-matrix method was applied to solve the optical equation. The solutions allowed plotting the optical reflectivity as a function of wavelengths and layer thicknesses. The optical refractive index and thicknesses of considered materials, which allowed us to have the lowest reflection, were used to simulate the electrical properties of the cell, using the TCAD (2D)/ Silvaco Atlas software.

The following figure represents the optical reflectivity of each material under consideration. The refractive index database of each material used in the simulation as a function of the wavelength was taken from references [9], [10], [11] and [12].

Using a passivation layer on the front side of the cell implies a compromise between reflection, absorption and surface passivation. Indeed, it can be seen that, the thicker the dielectric layer, the smaller the surface recombination. However, when the dielectric layer thickness increases, a large part of radiation is absorbed and therefore lost.

It is therefore required to determine the optimum thickness of the dielectric layer that can passivate the substrate correctly. So, a thin passivation layer must lead to the best compromise between the optical (absorption and reflection) and the electrical losses (recombination).

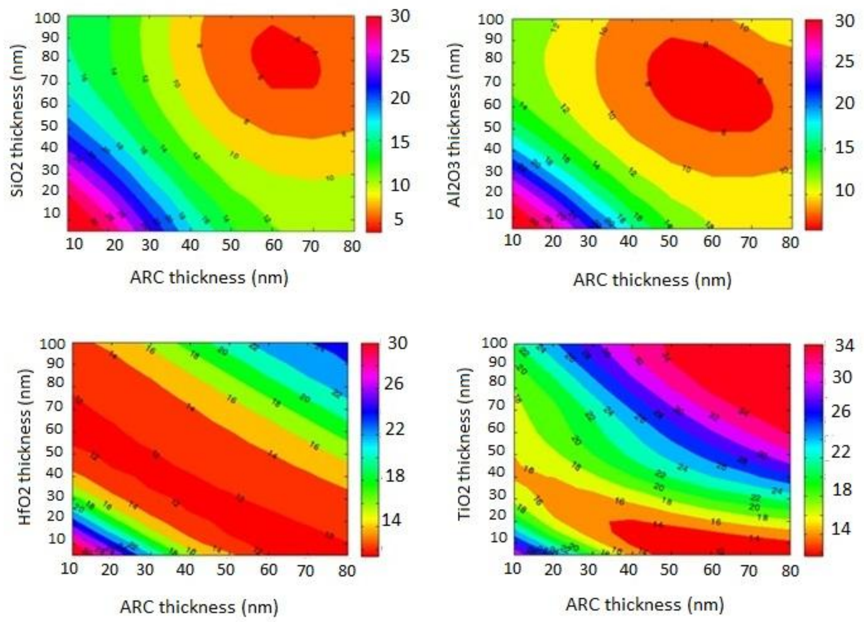


Figure 3: Reflectivity as a function of SARC thickness and dielectric thickness.

The optical losses due to reflection and absorption on the front side of the simulated mc-Si EWT solar cell, passivated with $Al_2O_3$, are evaluated and reported in the figure below.

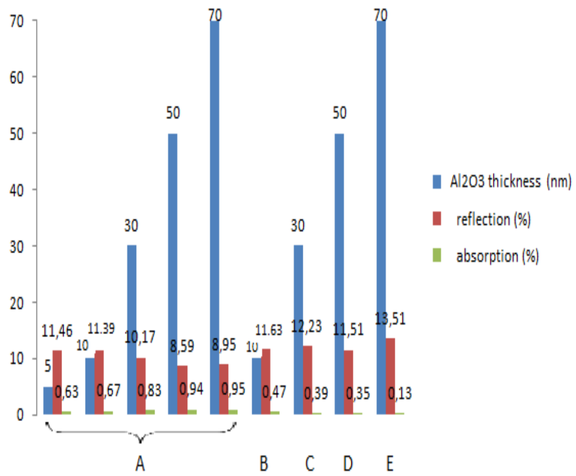


Figure 4: Optical losses of the simulated solar cell as a function of the variation of $Al_2O_3$ (dielectric layer) thickness and $SiN_x$ (SARC) thickness (A: 80nm, B: 60nm C: 40nm D: 30nm and E: 10nm).

Then, the electrical parameters, such as the short-circuit current and the solar cell efficiency of the simulated solar cell, as a function of the variation of $Al_2O_3$ (dielectric layer) thickness and $SiN_x$ (SARC) thickness are summarized in the figure below.

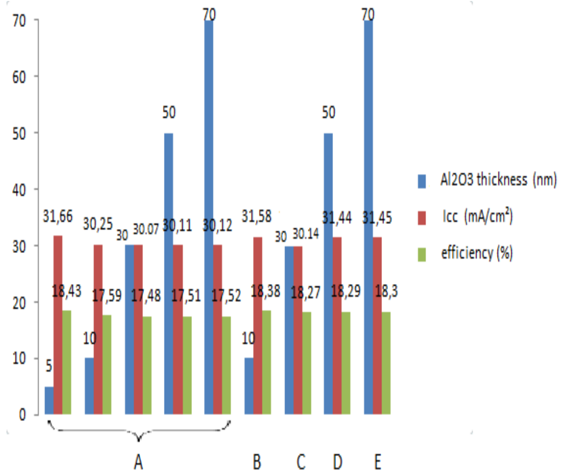


Figure 5: Electrical parameters of the simulated solar cell as a function of the variation of $Al_2O_3$ (dielectric layer) thickness and $SiN_x$ (SARC) thickness (A: 80nm, B: 60nm C: 40nm D: 30nm and E: 10nm).

For $Al_2O_3$, the maximum efficiency obtained was 18.43 % (less than the efficiency of a p-type EWT multi crystalline silicon solar cell without front surface passivation). Figures 6, 7 and 8 show the variation of the optical losses (reflection and absorption) and the electrical parameters (short-circuit current and solar cell efficiency) of the simulated cell as a function of the thicknesses of different dielectrics ($HfO_2$, $TiO_2$ and $SiO_2$) and the thickness of $SiN_x$ (SARC).

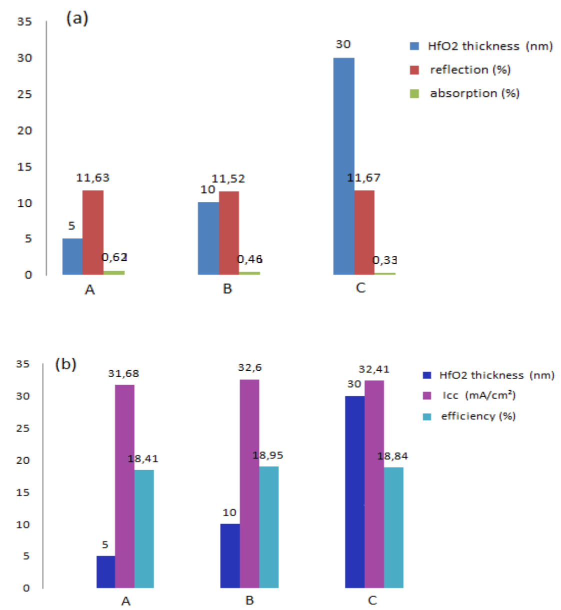


Figure 6: Variation of the optical losses (a) and electrical parameters (b) of the simulated cell with the variation of $HfO_2$ (dielectric layer) thickness and $SiN_x$(SARC) thickness(A: 80nm, B: 60nm and C: 40nm).

For $HfO_2$, good passivation properties were found. For a 10 nm thick dielectric layer and a 60 nm thick SARC, the short-circuit current achieved was about 32.6 mA/cm$^2$ and the energy conversion efficiency around 19%.

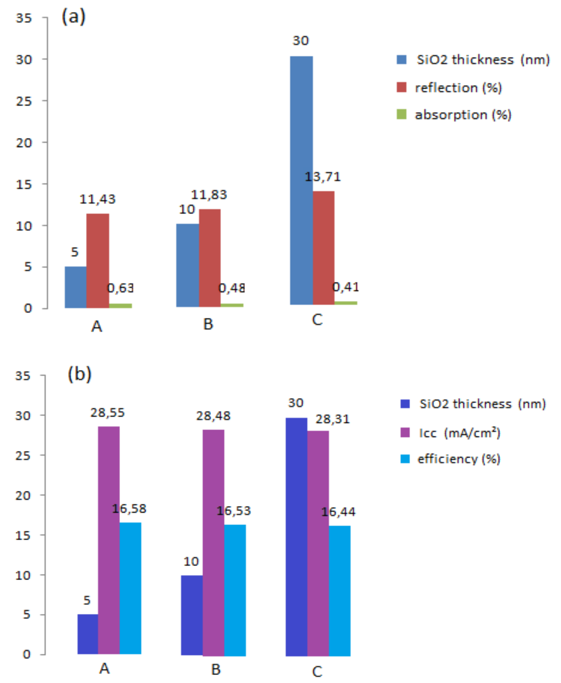


Figure 7: Variation of optical losses (a) and electrical parameters (b) of the simulated cell with the variation of $SiO_2$ (dielectric layer) thickness and $SiN_x$ (SARC) thickness (A: 80nm, B: 60nm and C: 40nm).

For $SiO_2$ the electrical parameters degrade, especially the short-circuit current which decreases by about 6.75 mA/cm². This degradation is mainly caused by the diffusion of atomic hydrogen to the $SiO_2$-Si interface. From the simulation results, such degradation can only be explained by the increased recombination rate on the front.

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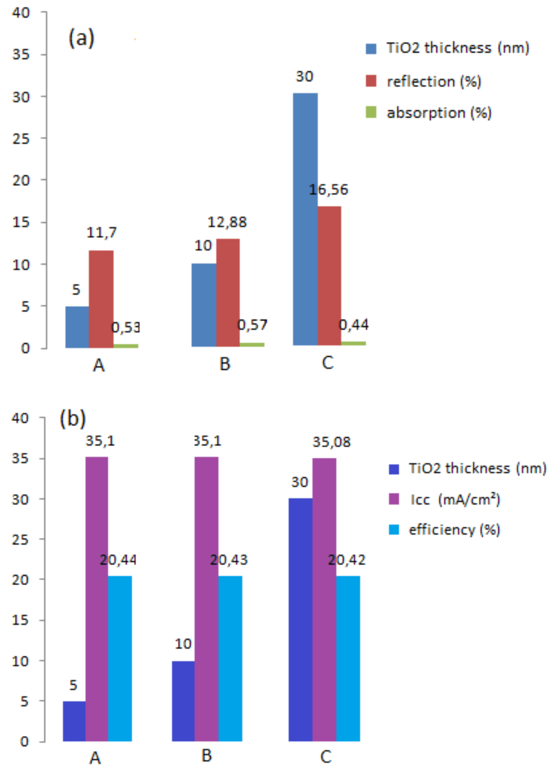


Figure 8: Variation of optical losses (a) and electrical parameters (b) of the simulated cell with the variation of $TiO_2$ (dielectric layer) thickness and $SiN_x$ (A: 70nm, B: 70nm and C: 40nm).

For $T_iO_2$, the implied open-circuit voltage approximated 0.7 V, the short circuit current obtained exceeded 35 mA/cm² and an energy conversion efficiency of 20.44% was reached. This efficiency improvement can be explained by the decreased recombination rate on the front of the cell.

The table below summarizes the optical losses (reflection and absorption) and the electrical parameters (short circuit current, open-circuit) voltage) and solar cell efficiency) of the considered EWT solar cell, for the four materials, with optimized thicknesses.

| Dielectric oxide | Ref cell | $Al_2O_3$ | $HfO_2$ | $SiO_2$ | $TiO_2$ |
|---|---|---|---|---|---|
| oxide thickness (nm) | / | 5 | 10 | 5 | 5 |
| SiNx ARC thickness (nm) | 80 | 80 | 60 | 80 | 70 |
| Losses (%) by reflexion | 10.32 | 11.46 | 11.52 | 11.43 | 11.70 |
| Losses (%) by absorption | 0.59 | 0.63 | 0.46 | 0.63 | 0.53 |
| $I_{cc}$ (mA/cm²) | 32.32 | 31.66 | 32.60 | 28.55 | 35.10 |
| $V_{oc}$ (V) | 0.680 | 0.697 | 0.696 | 0.694 | 0.699 |
| η (%) | 18.51 | 18.43 | 18.95 | 16.58 | 20.44 |

Table 5: Variation of the optical losses and electrical parameters of the simulated cell with the variation of dielectric materials and $SiN_x$ (SARC) (best results).

Another way to confirm the above results is to plot the variation of the External Quantum Efficiency (EQE) for different dielectric materials, knowing that EQE is the ratio of the number of charge carriers collected by the cell to the number of incident photons (coming from the outside). The surface recombination velocity (SRV) affects the variation of EQE. Higher SRV means that the generation rate of charge carriers in the considered solar cell decreases.

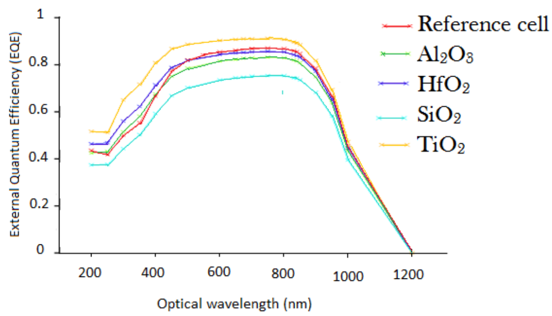


Figure 9: Variation of EQE with different dielectric materials (using TCAD Silvaco/Atlas software).

## 6. Conclusion

Surface passivation is an extremely important process for high-efficiency silicon solar cells, especially on the front surface where most of the light is collected. Significant differences were observed in the surface passivation of p-type EWT multi crystalline silicon solar cells when $Al_2O_3$, $HfO_2$, $TiO_2$ and $SiO_2$ were used.

A priori, thermal $SiO_2$ did not lead to a good performance of the EWT solar cell. The $SiO_2$ layer does not allow obtaining a good passivation. $HfO_2$ and $Al_2O_3$ show good front passivation properties.

To conclude, an average energy conversion efficiency of 20.5% was reached with a (10 x 10) cm² p-type multi crystalline silicon solar cell, with $TiO_2$ as a dielectric layer for surface passivation. An implied open-circuit voltage equal to 0.7 V was obtained. The high refractive index of $TiO_2$ (n ≈ 2.6 at λ = 620 nm), which is extremely close to the optimal refractive index of a silicon solar cell under glass (n = 2.43 at λ = 600 nm) [15], is therefore interesting for increasing the cell efficiency.


## Acknowledgements

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