

## MULTI-LAYER TCO BASED ANTI-REFLECTIVE COATINGS FOR SILICON SOLAR CELLS

D.N. Wright<sup>1</sup>, A. Ulyashin<sup>2</sup>, A. Bentzen<sup>3</sup>, E.S. Marstein<sup>1</sup>, A. Holt<sup>1</sup>

<sup>1</sup>Section for Renewable Energy, Institute for Energy Technology, P.O. Box 40, NO-2027 Kjeller, Norway

<sup>2</sup>University of Oslo, Center for Material Science and Nanotechnology, P.O. Box 1048 Blindern, NO-0316 Oslo, Norway

<sup>3</sup>Renewable Energy Corp. ASA, Veritasveien 14, P.O. Box 280, NO-1323 Høvik

e-mail: danielnw@ife.no

**ABSTRACT:** Transparent conducting oxides, such as Indium-Tin Oxide (ITO) layers, are widely used as combined anti-reflection coatings (ARC) and transparent electrodes on silicon (Si) based solar cells. However, the usefulness of an ITO ARC is limited by a lack of surface passivation combined with a non-negligible absorption. A promising prospect is the use of multi-layer approaches, where films of different materials, some of which yield passivation, are combined. In this paper, the results of optical simulations of 4 different possible designs incorporating ITO, silicon nitride ( $\text{SiN}_x\text{:H}$ ) and silicon oxide ( $\text{SiO}$ ) are presented. The best design improved the transmittance into the Si solar cell by 10% absolute compared to an ITO ARC. It was also found that these designs were very insensitive to variations in the  $\text{SiN}_x\text{:H}$  thickness,  $\text{SiO}$  thickness and  $\text{SiN}_x\text{:H}$  refractive index.

**Keywords:** Antireflection Coating, Simulation, ITO

### 1. INTRODUCTION

Both conventional homojunction solar cells with diffused-emitters and heterojunction solar cells have been made using Indium-Tin Oxide (ITO) as a combined anti-reflection coating (ARC) and transparent electrode [1]. However, the usefulness of an ITO ARC is limited by a lack of surface passivation combined with a non-negligible absorption. The optical and passivation properties of the ARC can be improved by including an intermediate layer between the ITO and the Si substrate. This thin layer can consist of amorphous Si (a-Si:H) (as used in SANYO's HIT solar cells [2]) or Si nitride ( $\text{SiN}_x\text{:H}$ ), both of which can be deposited by plasma enhanced chemical vapour deposition (PECVD).

In this paper we have simulated the spectroscopic transmittance through a multi-layer structure consisting of  $\text{SiN}_x\text{:H}$ , ITO and Si oxide ( $\text{SiO}$ ). By iteratively varying the thicknesses of the layers as well as the refractive index ( $n$ ) of the  $\text{SiN}_x\text{:H}$  layer, we were able to establish an optimized structure with respect to the total transmittance and, hence, the estimates of the obtainable short circuit current of a solar cell using this structure as an ARC and passivating layer.

### 2. EXPERIMENTAL

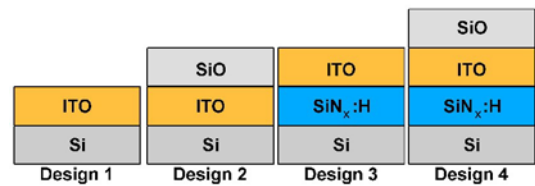
#### 2.1 Simulation method

Optimised ARC structures for unencapsulated cells were obtained by iteratively varying the thicknesses ( $d$ ) of all the layers and the  $n$  and the extinction coefficient ( $k$ ) of the  $\text{SiN}_x\text{:H}$  layer. Table I lists the ranges and resolutions for the iterations.

For every iteration the spectral transmittance,  $T(\lambda)$ , was calculated for wavelengths ranging from 300nm to 1150nm using the Matrix Method [3]. By calculating  $T(\lambda)$  instead of spectral reflectance, absorption in the layers was taken into account.

**Table I:** The iteration ranges of the simulation parameters

	Min	Max	increment
$d_{ITO}$ (nm)	0	80	2
$d_{SiN}$ (nm)	0	90	2
$d_{SiO}$ (nm)	0	120	2
$n_{SiN:H}$	1.94	3.15	~0.01



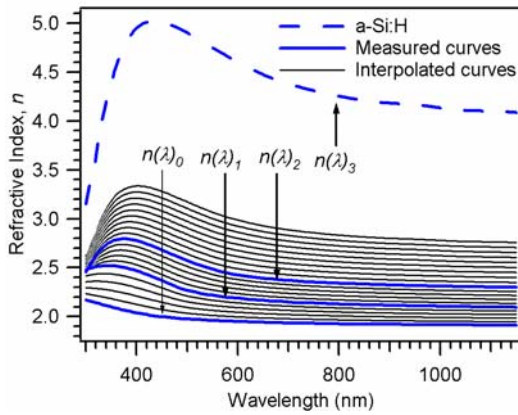
**Figure 1:** Designs simulated in this study

The total transmittance,  $T$ , was calculated from  $T(\lambda)$  by weighting against [4] the AM1.5 spectral irradiance standard. By including layer thicknesses of zero in the iterations, four different ARC designs were considered. These designs are summarised and named in figure 1. Design 1 consisted solely of ITO on Si and was used to illustrate the best optical performance obtainable with ITO on Si. Design 2 included  $\text{SiO}$  on top of the ITO layer in design 1 to enhance the optical performance. Design 3 included a  $\text{SiN}_x\text{:H}$  passivating layer in between the Si and ITO in design 1 and design 4 included  $\text{SiO}$  on top of design 3.

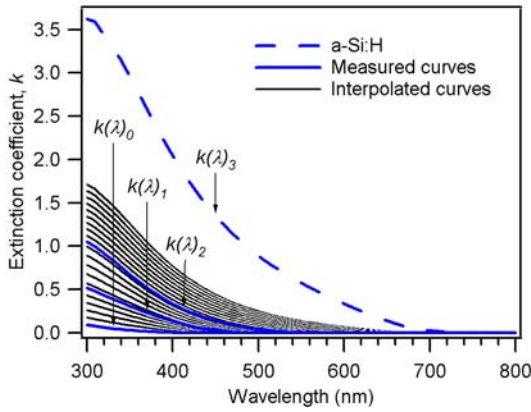
#### 2.2 Dispersion Relationships

The use of PECVD with silane ( $\text{SiH}_4$ ) and ammonia ( $\text{NH}_3$ ) as process gases allows adjustments of the complex refractive index ( $\tilde{n} = n + ik$ ) of deposited  $\text{SiN}_x\text{:H}$  by varying the  $\text{SiH}_4/\text{NH}_3$  ratio. Increasing the ratio creates  $\text{SiN}_x\text{:H}$  films with higher Si content and higher  $\tilde{n}$ . Omitting  $\text{NH}_3$  altogether allows for the deposition of a-Si:H.

For adequate resolution in  $\tilde{n}$ , many sets of  $\tilde{n}$  dispersion relationships ( $\tilde{n}(\lambda)$ ) for the wavelength ( $\lambda$ ) range from 300nm to 1150nm were needed.



**Figure 2:** Measured and interpolated refractive index curves



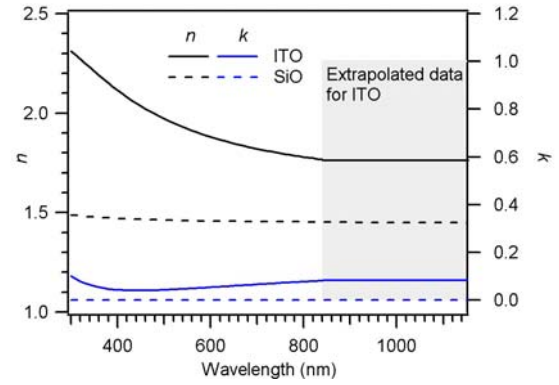
**Figure 3:** Measured and interpolated extinction coefficient curves

These sets were interpolated between known  $\tilde{n}(\lambda)$ , where two sets of  $\tilde{n}(\lambda)$  were used as lower and upper limits while two additional sets were used as intermediate guides. The lower limit,  $\tilde{n}(\lambda)_0$  and the intermediate guides,  $\tilde{n}(\lambda)_1$  and  $\tilde{n}(\lambda)_2$ , were obtained by spectroscopic ellipsometry on PECVD  $\text{SiN}_x\text{:H}$  with a various  $\text{SiH}_4/\text{NH}_3$  ratios. For the upper limit,  $\tilde{n}(\lambda)_3$ , data for a-Si:H was used. The  $\tilde{n}(\lambda)$  sets, shown in figure 2 and 3, required for the calculations were thus interpolated between  $\tilde{n}(\lambda)_0$  and  $\tilde{n}(\lambda)_1$ ,  $\tilde{n}(\lambda)_1$  and  $\tilde{n}(\lambda)_2$  and  $\tilde{n}(\lambda)_2$  and  $\tilde{n}(\lambda)_3$ , by

$$\begin{aligned} \tilde{n}_i(\lambda) &= n_i(\lambda) + ik_i(\lambda) = \\ &n(\lambda)_j \times (1-x) + n(\lambda)_{j+1} \times x + \\ &i(k(\lambda)_j \times (1-x) + k(\lambda)_{j+1} \times x) \end{aligned} \quad (1)$$

where  $x$  is varied from 0 to 1.

For Si, SiO, ITO and a-Si:H,  $\tilde{n}(\lambda)$  was taken from the material database of the optical simulation software ‘‘Essential MacLeod’’, by Thin Films Center [5]. The origins of this data was not specified. The  $\tilde{n}(\lambda)$  for SiO and ITO are shown in figure 4.



**Figure 4:** The dispersion relationships for ITO and SiO

There are two factors that brought some uncertainty to the simulations;

- The  $\tilde{n}(\lambda)_{ITO}$  ranges only to  $\lambda=850\text{nm}$  and values for higher  $\lambda$  could not be found in the literature. It was thus assumed that  $\tilde{n}(\lambda > 850\text{nm}) = \tilde{n}(\lambda = 850\text{nm})$ . This assumption may have brought an uncertainty to the simulations since 25% of the photons in the interval  $300\text{nm} < \lambda < 1150\text{nm}$  in the AM1.5 spectrum occur at  $850\text{nm} < \lambda < 1150\text{nm}$ .
- As with  $\text{SiN}_x\text{:H}$ ,  $\tilde{n}(\lambda)_{ITO}$  can be varied by the deposition conditions, albeit to a much smaller extent. Although the largest variation seems to occur in  $k$  mainly above  $500\text{nm}$  [1], this may still entail that the simulation over- or underestimate the absorption in the ITO layer.

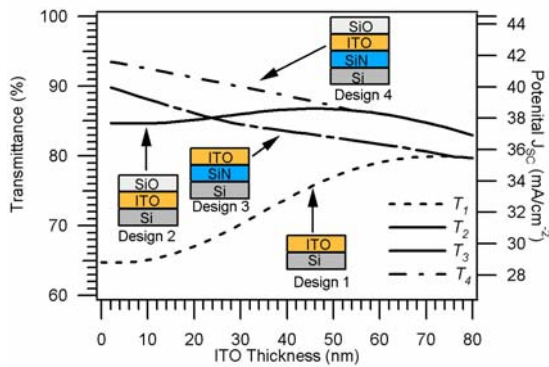
Any quotes of  $n$  in this paper refer to the value of  $n$  at  $\lambda = 633\text{nm}$ , unless otherwise specified.

## 3. RESULTS

### 3.1 $T$ versus ITO thickness

Figure 5 displays the maximum obtainable  $T$  for the four designs,  $T_1$ ,  $T_2$ ,  $T_3$  and  $T_4$  against the ITO layer thickness,  $d_{ITO}$ .

To obtain  $T_1$ , all thicknesses but  $d_{ITO}$  were kept at zero.  $T_1$  reached a maximum of 80% at  $d_{ITO} = 72\text{nm}$ , which corresponds to a potential short circuit current density ( $J_{SC}$ ) of around  $35\text{mA}/\text{cm}^2$ , disregarding any other  $J_{SC}$  losses in the solar cell. As ITO does not passivate the Si surface or bulk, one can expect significant losses due to charge carrier recombination. Hence there lay significant potential for enhancement in combining ITO with other film materials, both in an optical and passivation perspective.



**Figure 5:** Maximum obtainable transmittance for the 4 designs considered versus ITO layer thickness

Design 2, 3 and 4 gave higher transmittance due to the anti-reflective properties of SiO and SiN<sub>x</sub>:H. In the case of design 2, the increase in  $T_2$  with  $d_{ITO}$  was mainly due to the fact that the onset of absorption in the ITO layer was overcompensated by the decreased surface reflectance caused by the ITO/SiO stack structure. At  $d_{ITO} = 50\text{nm}$ ,  $T_2$  reached a maximum of 87%, 7% absolute above the best value of  $T_1$ .

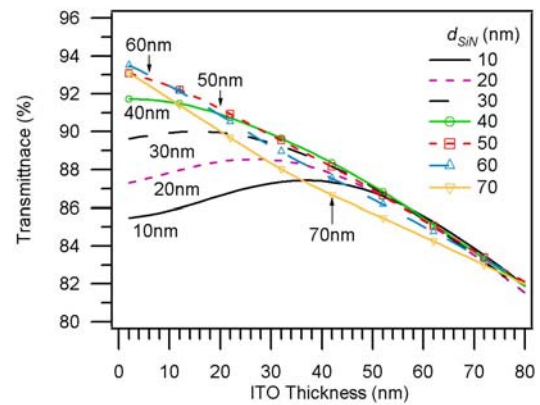
As SiN<sub>x</sub>:H has better anti-reflective properties than SiO, design 3 gave a higher transmittance than design 2 for low values of  $d_{ITO}$ . However, unlike in design 2, the onset of absorption in the ITO layer was not compensated by lower reflectance of the SiN<sub>x</sub>:H/ITO stack. Additionally, the  $\tilde{n}(\lambda)_{SiN_x:H}$  increased, leading to increased absorption in the SiN<sub>x</sub>:N layer. These two factors lead to a monotonous decrease in  $T_3$  as  $d_{ITO}$  was increased.

Design 4 performed best of all the designs due to the reduction in reflectance by adding the SiO layer on top of ITO. This reduction in reflectance however was counter balanced by the need for a higher  $\tilde{n}_{SiN_x}$ , which lead to an estimated absorption in the SiN<sub>x</sub>:H layer of 2.4% at  $d_{ITO} = 0\text{nm}$ . As  $d_{ITO}$  increased to 30nm,  $d_{SiN_x}$  decreased from 60nm to 44nm while  $\tilde{n}_{SiN_x}$  increased from 2.17 to 2.31. The resultant design resulted in a reflectance of only 3.2%, but a significant increase in absorption to 6.8%. However, at  $d_{ITO}=30\text{nm}$ , design 4 still performs better optically than any of the other designs. At  $d_{ITO}=50\text{nm}$ ,  $T_4$  converges with  $T_2$ , indicating that there is no advantage with respect to optical performance of the ARC of having the intermediate SiN<sub>x</sub>:H layer above this value of  $d_{ITO}$ .

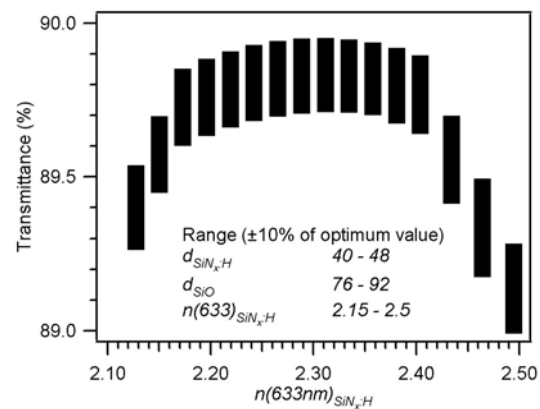
### 3.2 $T$ versus SiN<sub>x</sub>:H and ITO thicknesses

Figure 6 shows  $T_4$  versus  $d_{ITO}$  for different values of  $d_{SiN_x}$ . In order to obtain  $T > 90\%$ ,  $d_{ITO}$  must be below 30nm and  $d_{SiN_x}$  can be between 30nm and 70nm.

One positive point with this design is the relative insensitivity to variations in  $d_{SiN_x}$ ,  $d_{SiO}$  and  $n_{SiN_x}$  when  $d_{ITO}=30\text{nm}$ . Changes of  $\pm 10\%$  in these parameters lead only to a decrease in  $T_4$  of 1% absolute. By keeping  $n_{SiN_x}$  within  $\pm 5\%$ , the decrease is only 0.4% absolute, as can be seen from figure 7.



**Figure 6:**  $T_4$  versus  $d_{ITO}$  for different  $d_{SiN}$



**Figure 7:** Tolerance analysis with respect to  $d_{SiN}$ ,  $d_{SiO}$  and  $n_{SiN}$  for  $d_{ITO}=30\text{nm}$ . The columns include all obtainable  $T_4$  for the values of  $d_{SiN}$  and  $d_{SiO}$  which lie within  $\pm 10\%$  of the optimum values.

For comparison, a similar simulation for an ARC with only SiN<sub>x</sub>:H revealed that a 10% change in  $d_{SiN}$  and  $n_{SiN}$  resulted in a decrease of  $T$  of up to 4% absolute. Thus it can be concluded that multi-layer ARC structures are more tolerant to variations in the thicknesses and refractive index of the individual layers.

## 4. DISCUSSION

There are three important questions that arise from design 4:

- How thick must the SiN<sub>x</sub>:H layer be in order to effectively passivate the Si surface?
- How thin must the SiN<sub>x</sub>:H layer be in order for electrons to tunnel through to the ITO?
- How thick does the ITO layer have to be in order to conduct to such a degree that it can be used as an advantage in the design?

The minimum  $d_{SiN}$  needed to obtain good surface passivation has been found to be between 20nm and 40nm [6,7]. This correlated well with the thickness needed for good optical performance of design 4. It must be noted, however that the SiN<sub>x</sub>:H films become more sensitive to thermal processes as they become thinner [7].

As to the second question, in principle the answer should be as thin as possible, as SiN<sub>x</sub>:H is an insulator. Previously, thin layers (~10nm) of both SiO and a-Si

have been used to passivate the Si surface for cells using ITO as an ARC. At this thickness, electrons are able to tunnel through the passivating layer and into the conducting ITO. As can be seen from figure 6, however, utilising a  $d_{SiN}$  of 10nm will only lead to a potential  $T$  of 87% and may also not lead to any passivation, as discussed above. However, a recent development in ITO deposition [8] may open for the possibility of conducting electrons through even thicker insulating films without sacrificing the optical performance.

As to the third question, studies of ITO films deposited by magnetron sputtering have shown that the resistivity can be varied over several orders of magnitude by varying deposition parameters, such as the oxygen content [9], deposition pressure [10] and temperature [11,12]. Resistivities as low as  $1.8 \times 10^{-4} \Omega \text{ cm}$  have been reported for ITO films with  $\tilde{n}(\lambda)_{ITO}$  comparable to that used in this study [1]. Such a resistivity would constitute a sheet resistance of  $55 \Omega/\text{sq.}$  for a 30nm ITO layer, which is comparable to that of an industrial Si solar cell emitter. This sheet resistance might invoke the possibility of increasing the distance between the fingers in the grid, thus decreasing the total area covered by metal and decreasing the shadowing loss. An additional advantage to using even a thin ITO layer could be to collect current from areas in a multi crystalline Si solar cell that are surrounded by grain boundaries, which contain a large number of recombination sites.

Additionally, the deposition temperature for the above-mentioned ITO was only  $260^\circ\text{C}$ , which is lower than the standard deposition temperature for PECVD  $\text{SiN}_x\text{:H}$  and thus poses little risk of degrading a thermally sensitive thin  $\text{SiN}_x\text{:H}$  passivating layer.

## 5. CONCLUSION

The addition of  $\text{SiN}_x\text{:H}$  and  $\text{SiO}$  to an ITO ARC on a Si solar cell has been shown by iterative simulation to be optically advantageous compared to using only ITO. The inclusion of an intermediate  $\text{SiN}_x\text{:H}$  layer between the Si and ITO gave an increased transmittance through the ARC by reducing the surface reflection. The intermediate layer could also improve cell performance by passivating the surface and bulk of a mc-Si solar cell. Further optical enhancement could be made by adding a  $\text{SiO}$  layer on top of the ITO.

The structure's transmittance was found to be very insensitive to variations in the  $\text{SiN}_x\text{:H}$  and  $\text{SiO}$  thicknesses and well as the  $\text{SiN}_x\text{:H}$  refractive index, but very sensitive to changes in the ITO thickness.

Transmittances of over 90% were shown possible for ITO thicknesses of less than 30nm. This is 10% absolute higher than using only ITO as an ARC. At this thickness, a possible sheet resistance of  $55 \Omega/\text{sq.}$  could be obtained. The potential problem of including an insulating  $\text{SiN}_x\text{:H}$  layer between the Si and the ITO may be solved by recent developments in ITO deposition.

## 6. ACKNOWLEDGEMENTS

This work has been funded by the Research Council of Norway and REC Scancell AS.

## 7. REFERENCES

- [1] M. Losurdo et al., J. Vac. Sci. Technol. A 20 (2002) 37.
- [2] M. Taguchi et al., Proc. 31st IEEE Photovoltaic Specialist Conference (2005) 866
- [3] R.J. Martín-palma, J.M Martínez-duart and A. Macleod, IEEE Transactions On Education 43 (2000) 63.
- [4] D. N. Wright, E. S. Marstein And A. Holt, Proc. 31st IEEE Photovoltaic Specialist Conference (2005) 1237.
- [5] www.thinfilmscenter.com
- [6] A. Kenanoglu et al., Proc 19th European Photovoltaic Solar Energy Conference (2004) 1086.
- [7] T. Lauinger et al. , J. Vac. Sci. Technol. A 16 (1998) 530.
- [8] A.G. Ulyashin et al., Proc. 20th European Photovoltaic Solar Energy Conference, Barcelona (2005)
- [9] R.N. Joshi, V.P. Singh and J.C. McClure, Thin Solid Films 257 (1995) 32.
- [10] P. Canhola et al., Thin Solid Films 487 (2005) 271
- [11] S.H. Kim et al., Thin Solid Films 475 (2005) 262.
- [12] A. Rogozin et al., Thin Solid Films 496 (2006) 197.