Characterization of tunnel oxides in TOPCon solar cells

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Tunnel Oxide Passivating Contact (TOPCon) Cells

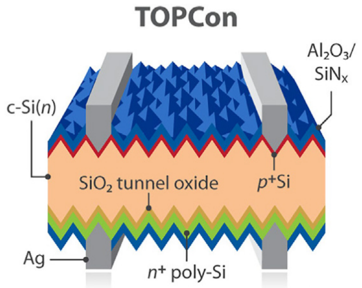


Figure 1 – TOPCon solar cell structure. From Verlinden et al. 2023

Tunnel Oxides

Two Main Functions:

1. ***Quantum Tunneling*** – Enables carrier movement across interface. Can be designed to favor one type of charge carrier over another via interaction with poly-Si [Fig. 3]. If barrier is too thick, tunneling stops
2. ***Passivation*** – Prevents formation of material defects at interface slowing the recombination rate of EHPs. If barrier is too thin, passivation is inadequate

TOPCon Structure

- Interface between the boron doped p^+ Si layer and the phosphorus doped c-Si wafer form a p/n junction where all electron/hole pairs (EHPs) are separated by carrier type
- Electrons gather at the back contacts and holes gather at the front contacts
- SiO_2 layer allows electrons to tunnel through; however, holes are blocked
- Al_2O_3/SiN_x layers passivate the poly-Si layers and provide anti-reflection coating

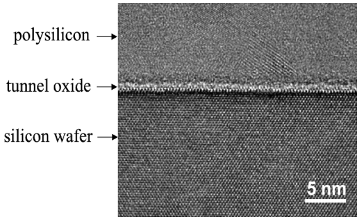


Figure 2 – TEM image of SiO_2 and poly-Si interface. From Tao et al. 2024

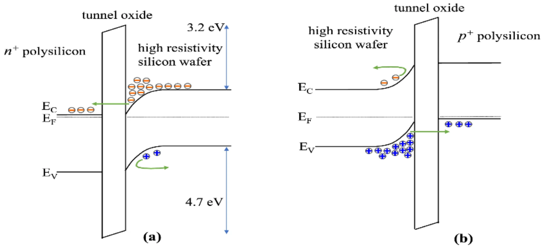


Figure 3 – Bandgap diagram detailing tunneling effect. From Tao et al. 2024

Tunnel Oxide Design Challenges

- Optical properties need to be well defined
- The SiO_2/c-Si interface can influence the optical behavior of thin-film SiO_2 layers
- Quantum tunneling probability is more sensitive to the width of a potential barrier than to the strength of the potential, so film thickness is the primary design parameter. Choi *et al.* found in their work that the optimal thickness is 1.2 – 1.5 nm

Spectroscopic Ellipsometry

Basics

- Light emitted from the lamp is linearly polarized and reflected off sample
- The reflection changes the polarization to elliptical [Fig. 5]
- Changes in received waves are analyzed to measure changes in amplitude and phase [Fig. 6]. This provides data for parameters Psi and Delta
- ***Psi(Ψ)*** – Relates amplitude of emitted vs. received waves
- ***Delta(Δ)*** – Relates phase difference of emitted vs received waves

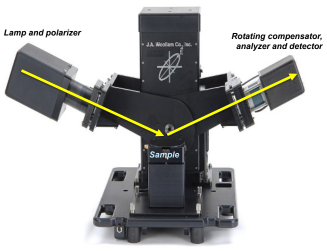


Figure 4 – M2000 Ellipsometer

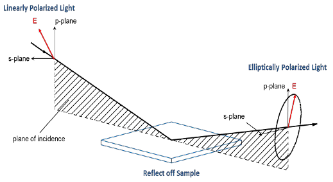


Figure 5 – Diagram detailing polarization change due to reflection

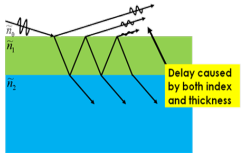


Figure 6 – Diagram detailing phase and amplitude change due to material thickness and index of refraction

Complex Reflection Ratio

- Defines the ratio (ρ) of the parallel ($\tilde{r}_P$) and perpendicular ($\tilde{r}_S$) components of light by the changes in amplitude and phase upon reflection

$$\tilde{\rho} = \frac{\tilde{r}_P}{\tilde{r}_S} = tan\Psi * e^{i\Delta}$$

$$r_p = \frac{N_{ti}^2 \cos\theta_i - (N_{ti}^2 - \sin^2\theta_i)^{1/2}}{N_{ti}^2 \cos\theta_i + (N_{ti}^2 - \sin^2\theta_i)^{1/2}} \qquad r_s = \frac{\cos\theta_i - (N_{ti}^2 - \sin^2\theta_i)^{1/2}}{\cos\theta_i + (N_{ti}^2 - \sin^2\theta_i)^{1/2}}$$

- $N_{ti} = N_t/N_i$ where N_i and N_t are the complex indices of refraction for the incident and transmission media
- θ_I – angle of incidence

Figure of Merit

- Analytical process to minimize the difference between the experimental data and optical model
- This difference is measured by the Mean Squared Error (MSE):

$$MSE = \sqrt{\frac{1}{3n-m}\sum_{i=1}^{n}\left[\left(\frac{N_{E_i}-N_{G_i}}{0.001}\right)^2 + \left(\frac{C_{E_i}-C_{G_i}}{0.001}\right)^2 + \left(\frac{S_{E_i}-S_{G_i}}{0.001}\right)^2\right]}$$

- *n* – number of experimental data points
- *m* – number of free parameters in model
- *E* – experimental value
- *G* – model value
- *N* – cos(2Ψ)
- C – sin(2Ψ)*cos(Δ)
- S – sin(2Ψ)*sin(Δ)

Optical Modelling

- Data analysis software is used to create models that match experimental data with the lowest possible MSE. This yields data on:
  1. Material thickness
  2. Index of refraction (n)
  3. Extinction coefficient (k)

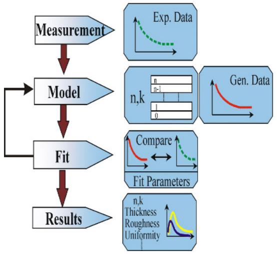


Figure 7 – Optical modelling flowchart

Optical modelling software CompleteEASE is used for all data analysis in this research. Provided by J.A. Woollam Company

Figures 4-7 from J.A. Woollam Company

Results

Tunnel Oxide Optical and Structural Properties

- Refractive index at 2 eV:
  1.82
- Thickness (nm):
  1.12
- MSE:
  1.5

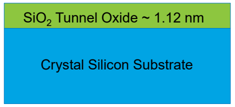


Figure 8 – Tunnel oxide sample structure

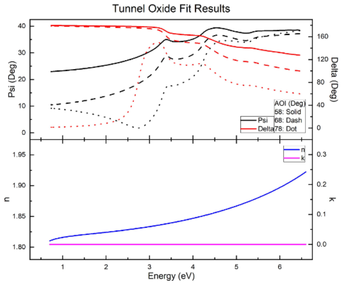
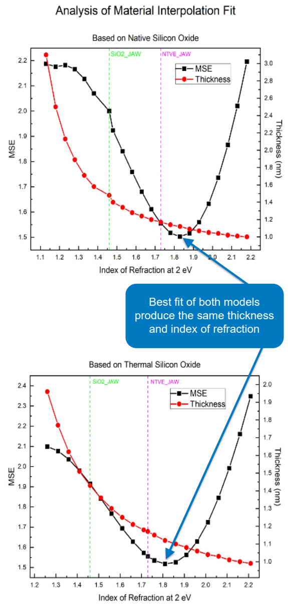


Figure 9 – Plot of tunnel oxide experimental and optical model data



Best fit of both models produce the same thickness and index of refraction

Figure 10 – Analysis of tunnel oxide index of refraction

Conclusion and Future Work

The 1.12 nm thickness for the tunnel oxide layer is near the optimal range described by Choi *et al*. This thickness should be effective at enabling quantum tunneling; however, it is slightly lower than the reported optimal range which could negatively impact the passivation of the poly-Si interface. An appropriate balance between the two functions must be met to optimize efficiency.

Follow up work could focus on testing the optimal range for tunnel oxide thickness in TOPCon solar cells, as well as improving the manufacturing process to produce better control of film thickness.

This work could be extended into more advanced TOPCon solar cells including double or triple stack structures, as well as experimental pinhole designs.

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