Rapid Quantification of Light Trapping in Bifacial Silicon Solar Cells Based on Inline Reflection Measurements

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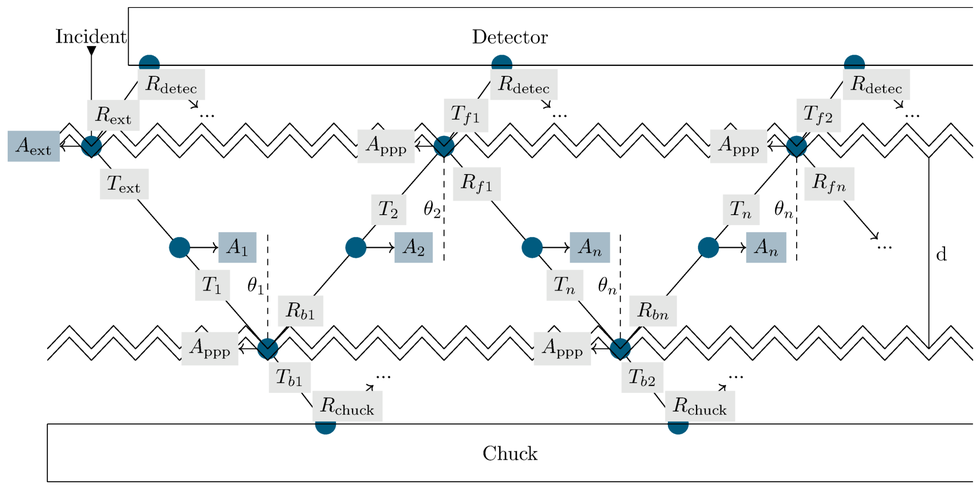
Introduction

- Analytical light trapping model of solar cells by Basore[1] and extensions[2,3]
  - Reflection R, transmission T and parasitic/active absorption pA/A
  - Suitable for common silicon based solar cells
- Fits to simple reflectance spectra suffer from overfitting
- Fits including information on R and T more stable and robust[4]
  ⇒ Inline measurements with direct model fits feasible

Effective Optical Light Trapping

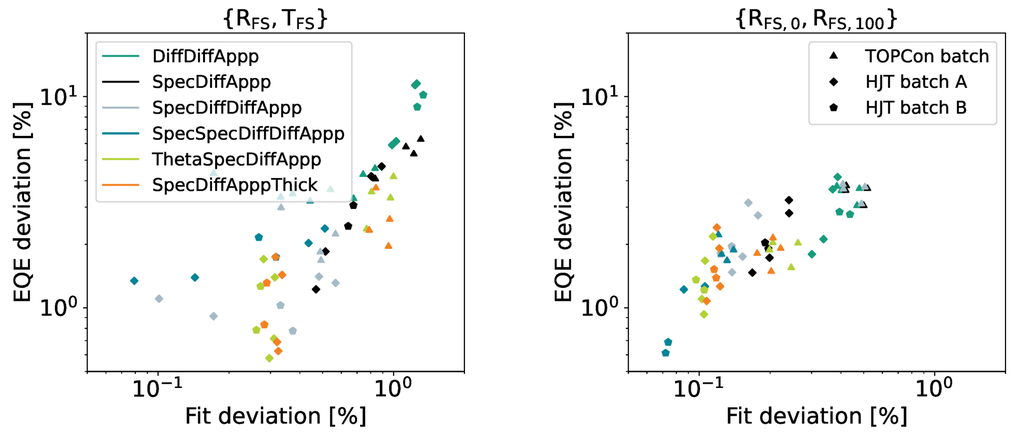
- Light absorption profile required as an input for electrical simulations
  - Used for example in PC1D, Quokka3 or PVLighthouse
- Reflection, transmission and external quantum efficiency (EQE) spectra
  - Information on light trapping at $\lambda > 950\ \mathrm{nm}$
- Calculation time of numerical fit procedure $t_{\mathrm{fit}} \approx 30\ \mathrm{ms}$



Sketch of effective analytical light trapping model originally proposed by Basore[1].

Fit Accuracy Analysis and Choice of Dataset

- Measurement data sets
  - Reflectance and transmittance $\{\mathrm{R_{FS}},\ \mathrm{T_{FS}}\}$
  - Reflectance on black and white backgrounds $\{R_{\mathrm{FS,0}},\ R_{\mathrm{FS,100}}\}$
- 6 sets of free fit parameters and 10 sample from industry and Fraunhofer ISE

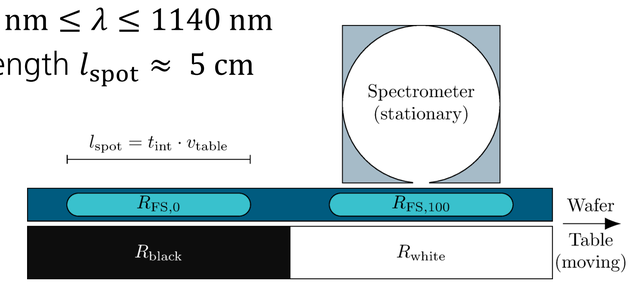


Correlation of „fit-quality" with „EQE-accuracy". Markers indicate cell type while colors distinguish sets of free parameters. Fits to $\{R_{\mathrm{FS}},\ T_{\mathrm{FS}}\}$ on the left side, and to $\{R_{\mathrm{FS,0}},\ R_{\mathrm{FS,100}}\}$ on the right side.

- 98th percentile of $|\vec{Y}_{\mathrm{meas}} - \vec{Y}_{\mathrm{model}}|$ as measure of deviation
- Correlation of "fit-quality" with deviations in EQE
  ⇒ Two reflection spectra on black and white background constrain fits well

Inline Measurement Setup

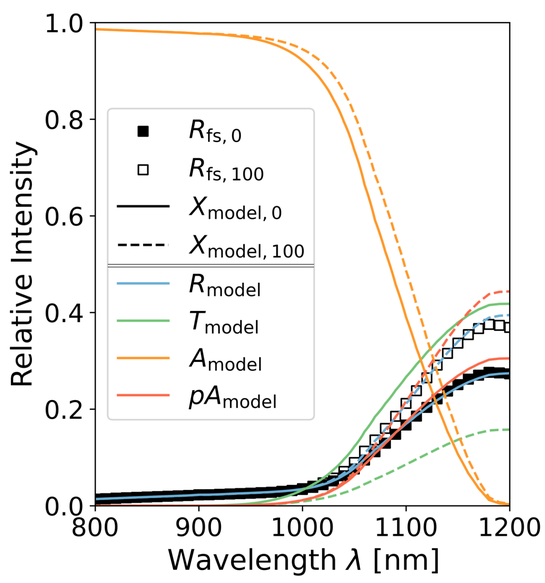
- Stationary detector with moving table
- Measurement wavelengths $360\ \mathrm{nm} \leq \lambda \leq 1140\ \mathrm{nm}$
- Spot width $w_{\mathrm{spot}} \approx\ 2\ \mathrm{cm}$ and length $l_{\mathrm{spot}} \approx\ 5\ \mathrm{cm}$
- Integration time $t_{\mathrm{int}} \approx\ 50\ \mathrm{ms}$



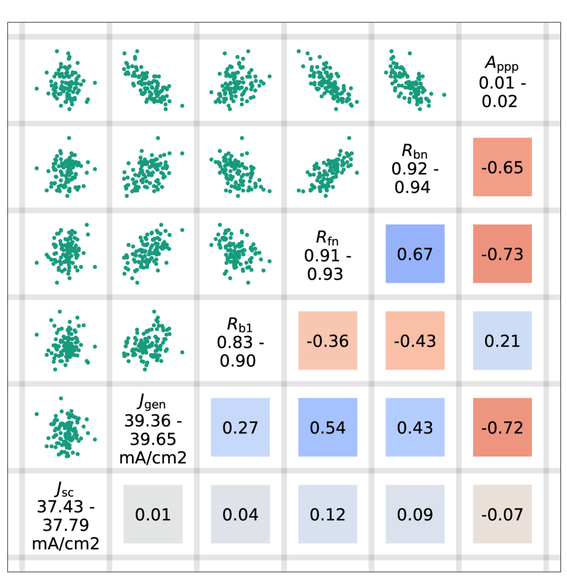
- Black and white background
  - $R_{\mathrm{black}}(\lambda) \approx 5\ \%$
  - $R_{\mathrm{white}}(\lambda) \approx 80\ \%$
- $R_{\mathrm{FS,0}}$ and $R_{\mathrm{FS,100}}$ together include necessary information on transmission

Example Fit and Inline Parameter Correlations

- Inline reflectance of 100 bifacial SHJ solar cells, M6+, $\eta \in [22.34, 22.54]\ \%$
- Combined least square fit of effective model to $R_{\mathrm{FS,0}}$ and $R_{\mathrm{FS,100}}$



Example fit to $R_{\mathrm{FS,0}}$ and $R_{\mathrm{FS,100}}$ with the corresponding modeled spectra.



Correlations of fit parameters, short circuit- and generation-current J_{SC} and J_{gen}. The transposed elements contain the correlation coefficients.

Results

- Good convergence for all cells
  - A_{ppp} as observed by Fell et al.[3], and $R_{\mathrm{int}} \approx 0.92$ for diffuse light[5]
- Highest impact on J_{gen} given by parasitic absorption parameter A_{ppp}
- Short circuit current J_{SC} not dominated by light trapping in example batch

Application

- Compressed information for inline modeling and characterization

Conclusion

→ Analytical chuck extension for light trapping models introduced
→ Stable model fits for reflectance on black and white backgrounds
→ Method validated on 100 bifacial silicon heterojunction solar cells
→ Possible application as input of inline characterization and digital twins

References:
1 P. Basore, "Extended spectral analysis of internal quantum efficiency", *IEEE*, 1993
2 R. Brendel et. al., "Theory of Analyzing Free Energy Losses in Solar Cells." *Applied Physics Letters*, 2008.
3 A. Fell et al., "Modeling parasitic absorption in silicon solar cells with a near-surface absorption parameter," *Solar Energy Materials and Solar Cells*, 2022
4 W. Wöhler et al., "Analyzing light trapping spectra including secondary reflections on the surrounding ," to be submitted, 2023
5 E. Yablonovitch, "Statistical ray optics," *Journal of Optical Society of America, 1982*

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link to Fraunhofer ISE contributions of the 40th EU PVSEC
https://ise.link/eupvsec2023
(available as of 20.09.2022)