Computational optical analysis of 3D modeled crystalline silicon substrates randomly textured

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Context

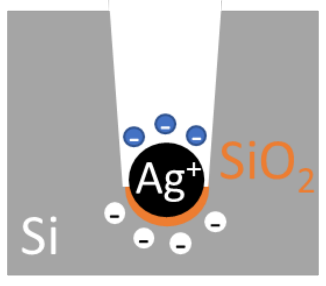
Optimized light trapping (LT) concepts have been explored in the last decades as a key path to enhance the solar cell efficiencies as it can increase significantly the optical absorption and thus the photocurrent generation densities (J_{sc}). This feature enables the usage of thinner and lower quality substrates. Among LT strategies, such as the use of diffraction gratings, photonic crystals, and optical resonators implementation, texturization by direct etching has been more commonly adopted due to its simplicity and cost associated. Particularly the metal-assisted chemical etching (MACE) method has demonstrated to be a practical solution for texturing crystalline silicon substrates.

In this work, we present a workflow to access the optical performance of texturized silicon substrates by MACE with no particular patterning and variable LT structures dimensions. The adopted MACE method uses a solution of hydrofluoric acid and hydrogen peroxide as etchants and a suspension of silver nitrate molecules. An extended experimental campaign showed the capability to produce extremely low reflective surfaces (∽3%). In order to evaluate the quality of the obtained nanostructures for solar cells application, finite-difference time-domain simulations (FDTD) were performed using 3D models of the textured substrates obtained from electron microscope (SEM) observations.

Method

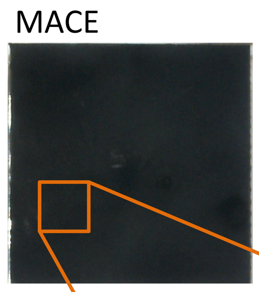
Metal-assisted chemical etching (MACE)

Principle's concept



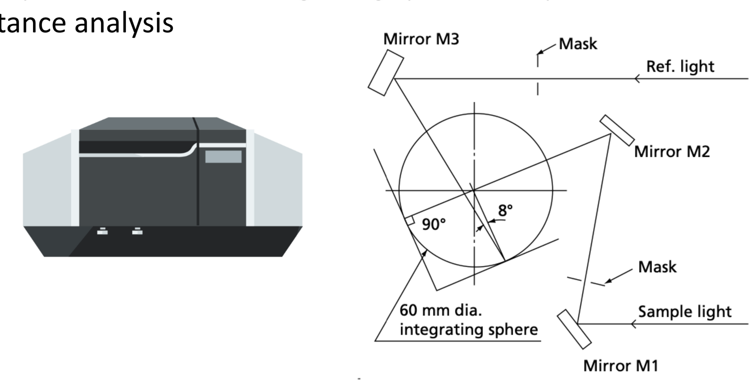
[Costa, Ivo, David Pera, and José A. Silva. "Improving light capture on crystalline silicon wafers." Materials Letters (2020): 127825.]

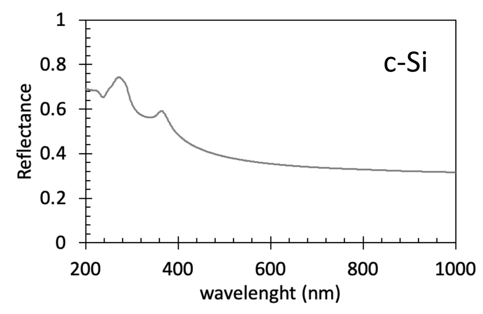
Black silicon sample obtained by MACE



Reflectance measurements

Spectrophotometer with integrating sphere for spectral reflectance analysis



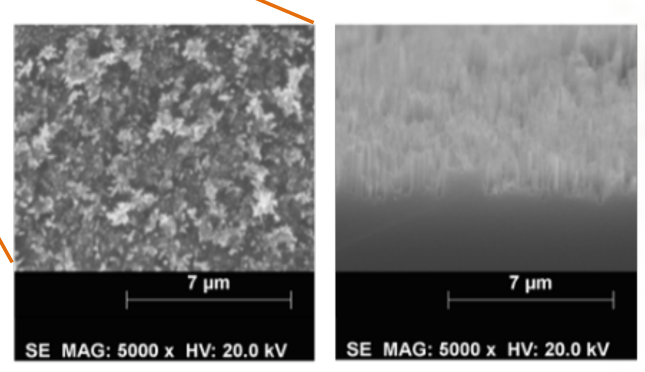


Validation

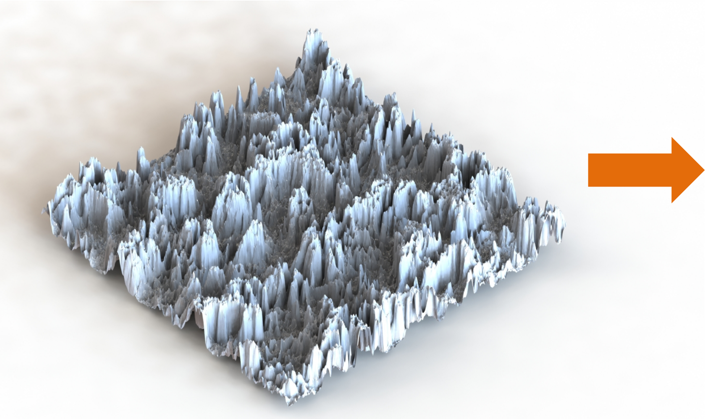
$$R_{\mathrm{eff}} = \frac{\sum_\lambda R_\lambda n_\lambda}{\sum_\lambda n_\lambda}$$

R_λ - Reflectance at wavelength λ
n_λ - Number of photons at wavelength λ (AM1.5)

Scanning electron microscopy



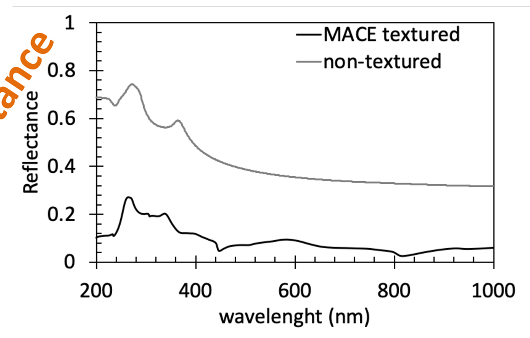
Surfaces' numerical 3D reconstruction

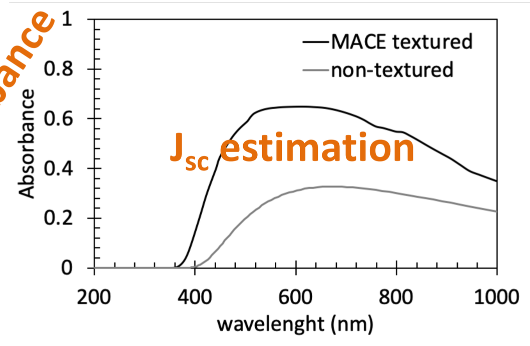


Surfaces modeling using several SEM images acquired with different angle views

Finite-difference time-domain simulations (FDTD)

Using a 3D Maxwell's Solver based software

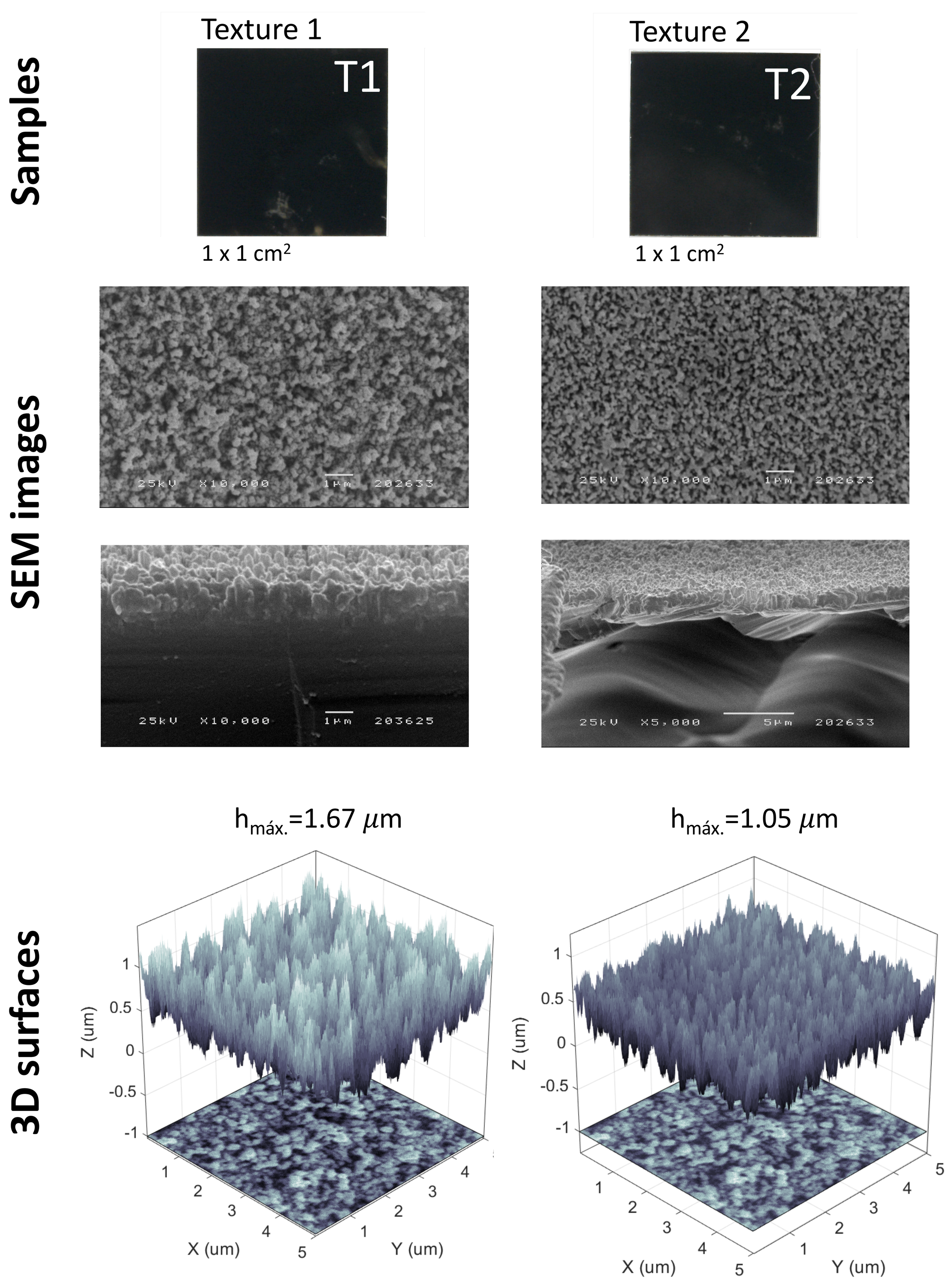




Results

Samples characterization

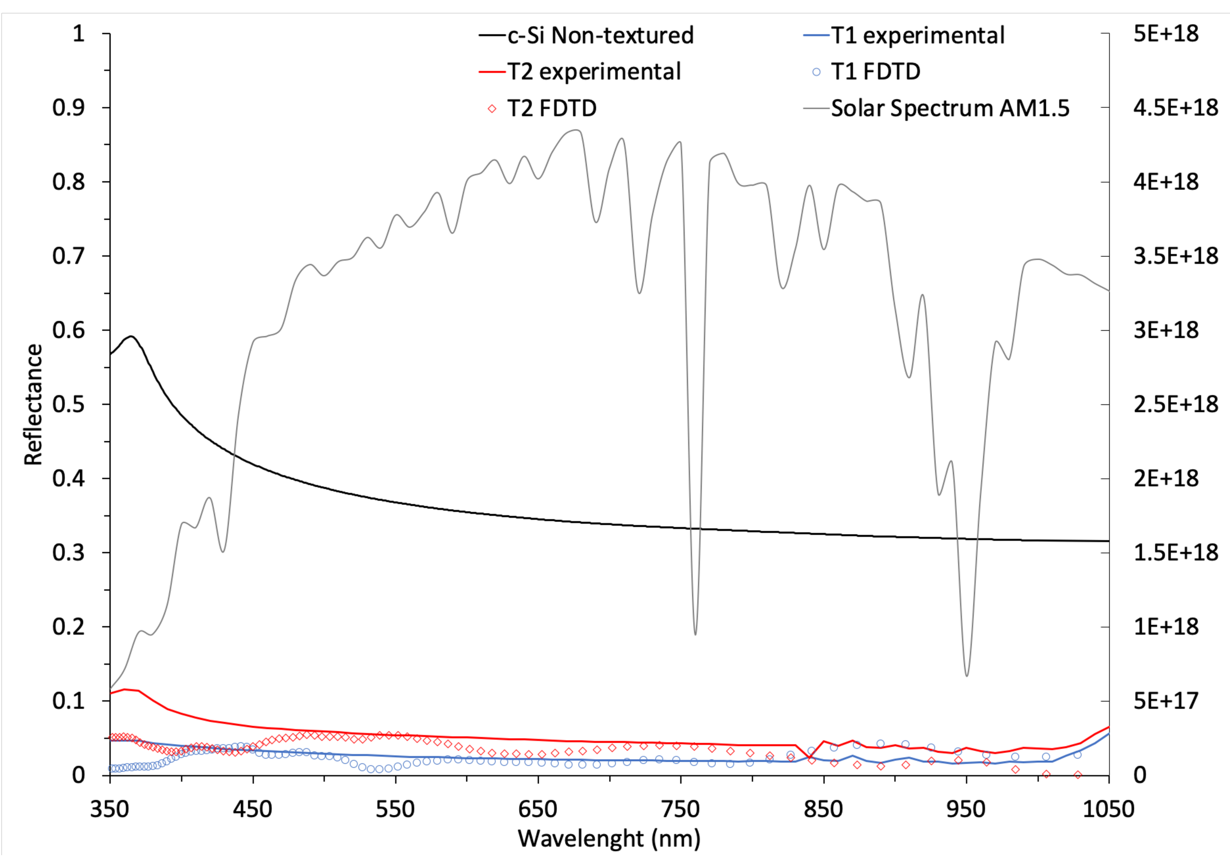
Example of two samples etched with different MACE solvent proportions.



FDTD simulations were performed for bulk thicknesses of 150 µm.

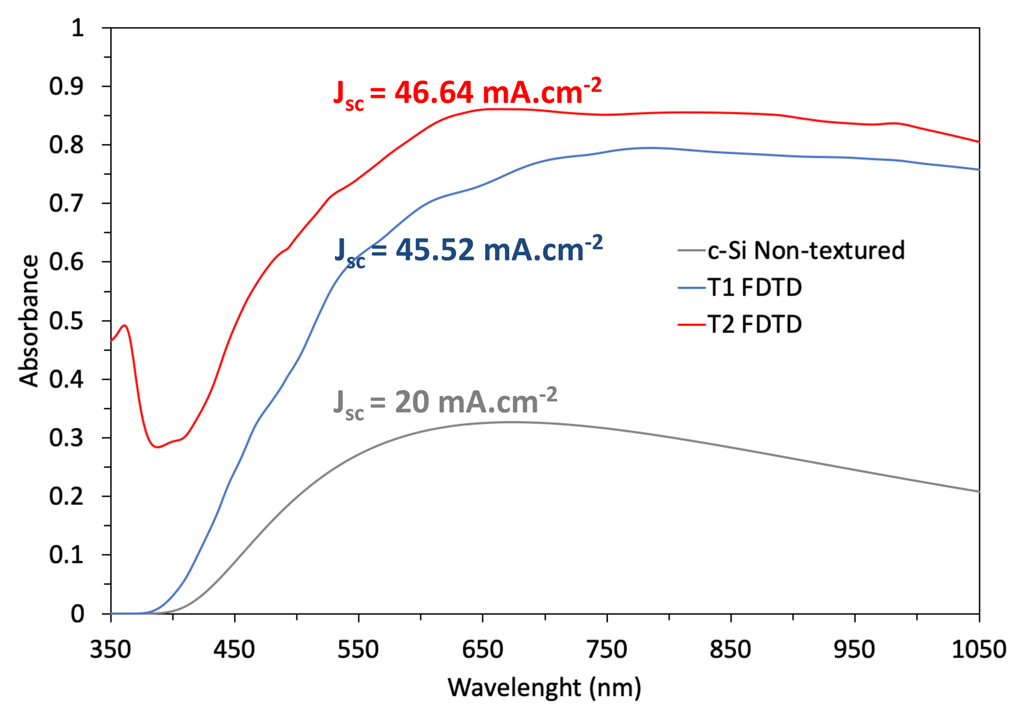
FDTD simulations results

Reflectance



An expressive decrease of the reflectance along the spectrum of interest was verified, which is consistent with the co-existence of both high- and low- aspect ratio structuring with the predominance of the second one.

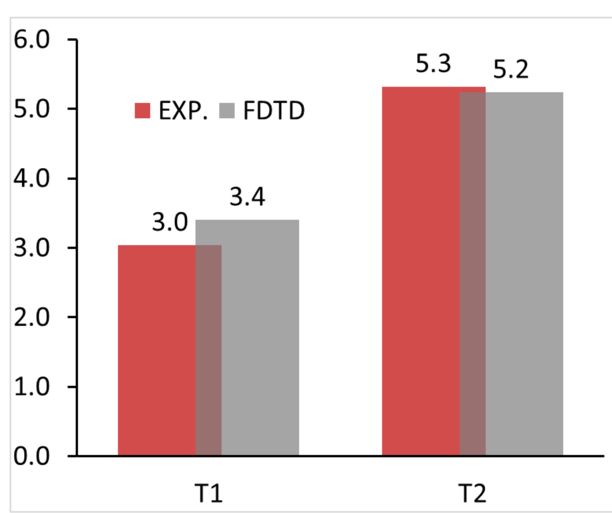
Absorbance



Simulated J_{sc} values indicate a potential to be increased more than 100% when compared with a non-texturized crystalline silicon substrate.

Effective Reflectivity

λ: 350 – 1050 nm



Wrap up

- The developed method was successfully validated by experimental comparison taking R_{eff} as figure-of-merit.
- The method can be used to improve the accuracy of the simulation of optical generation rates of complex textured surfaces in electro-dynamic simulations of photovoltaic devices.

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