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Optical simulation and analysis of iso-textured silicon solar cells and modules including light trapping

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Abstract

Solar cells made from multicrystalline silicon (mc-Si) wafers play an important role in photovoltaics. Nevertheless, tools for the optical simulation of these devices are scarce. In the present work, the reflectance and charge carrier generation of mc-Si cells and modules are for the first time simulated successfully in the complete spectral range including light trapping and escape light, as the comparison with measured reflectance of the finished cells and mini-modules shows. The "spherical caps" geometry is used to model the front surface reflection of iso-textured silicon solar cells. The characteristic angles of the spherical caps are determined from the reflectance of iso-textured wafers for three different texture strengths. Based on this calibration, the reflectance and charge carrier generation rates of cells encapsulated with EVA and glass are simulated and analysed. Iso-textured cells with full-area aluminium back surface field (Al-BSF) and with passivated emitter and rear (PERC) are quantitatively compared regarding the photo-generated current density j_{Ph}. The simulations demonstrate that the direct cell-to-module loss of iso-textured mc-Si cells with Al-BSF (0.7 mA/cm²) is smaller than for PERC cells (1.2 mA/cm²).

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Keywords: silicon solar cell; iso-texture; module; light trapping; raytracing

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1. Introduction

Conventional multi-crystalline silicon (mc-Si) and high-performance mc-Si [1] wafers have played and will play an important role in silicon photovoltaics with a market share of currently about 60% [2]. Within a typical industrial production sequence, wafers are textured by an isotropic etching process using HF/HNO_3 as acidic etchant, resulting in the so-called isotropic texture [3, 4].

Although the isotropic texture is widely used, tools for the optical simulation of this type of solar cells are scarce. Yang Li *et al.* [5] used spherical caps (see Fig. 1a) at the front and rear surface to simulate the optics of isotropically etched, bare mc-Si wafers. They stated that "the rear surface reflection model (…) will need to be further developed to more accurately represent the light trapping properties of final devices" [5]. Baker-Finch *et al.* [6] also chose the spherical-cap approach for the front surface. They demonstrated the validity of this approach also for varying angles of the incident light, but did not explicitly take reflection at the rear surface into account. Ingenito *et al.* [7] applied the spherical-cap approach, but had to introduce ad hoc an additional thin film to model the reflectance below 900 nm and had to assume an effective scattering angle of the light transmitted through the front surface. Peters *et al.* [8] applied the spherical-cap approach for a current loss analysis of a mc-Si solar module, but also had to neglect light trapping for the simulations.

In the present work, we overcome the compromises and drawbacks of the previous works. We implement the spherical-cap approach for the front surface reflection into the ray tracer of Sentaurus TCAD [9] and combine it with the Phong scattering model [10] and the tilted-mirrors approach [11, 12] for the internal rear surface reflection to describe the light trapping of Al-BSF and PERC rear sides, respectively. This, for the first time, constitutes a comprehensive optical simulation of mc-Si solar cells. The approach is calibrated to measured reflectance data of wafers and cells. The coupling gains and losses of encapsulated mc-Si cells are compared for Al-BSF and PERC rear sides.

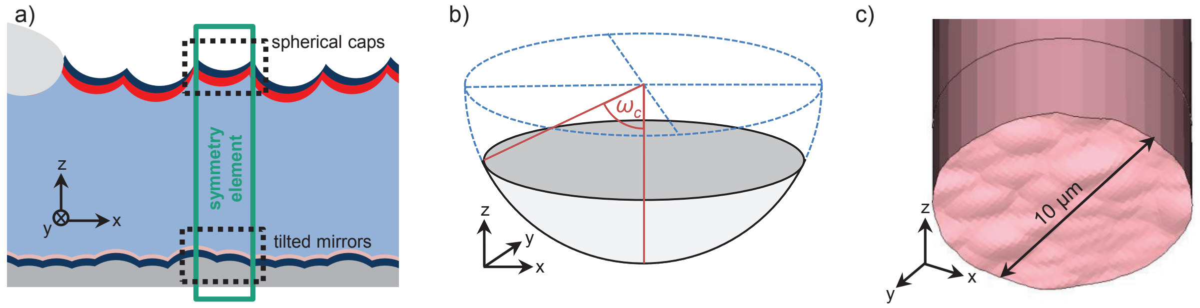

Fig. 1. a) Sketch of a mc-Si solar cell with the symmetry element of the optical simulation highlighted in green. The spherical caps and the tilted mirrors are highlighted by the black dotted rectangles. b) Sketch of the spherical-caps geometry and characteristic angle ω_c, c) CAD model of the tilted-mirrors approach for the PERC rear surface

2. Experimental

Three mc-Si wafers are wet-chemically textured in an HF/HNO_3 solution for three different times, resulting in the formation of three different surface textures which in the following are referred to as "strong", "medium" and "weak" isotropic texture. Micrographs after texturing are measured using an Olympus LEXT confocal microscope, see Fig. 2. The root-mean-square (RMS) roughness and the surface enlargement factor of the surfaces are summarized in Table 1. Two monocrystalline Si samples, one with planar surface and one with random-pyramid texture, serve as comparison.

Solar cells with full-area Al-BSF and screen-printed silver front metallization are manufactured from the wafer with medium isotropic texture within the PV-TEC [13]. The cell is then embedded between two 450 µm thin layers of EVA, covered by 3 mm thick module glass without anti-reflection coating, and a PPE back sheet to form single-cell mini-modules at Fraunhofer ISE's Module-TEC.

The spectral hemispherical reflectance is measured in three stages, after texturing, after the complete cell process and after module encapsulation on the cell area including fingers, but excluding busbars and back sheet.

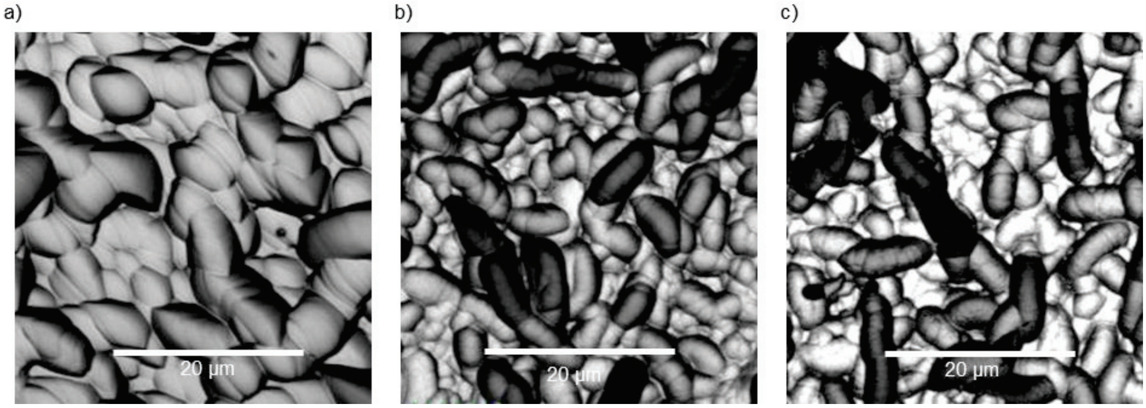

Fig. 2. Confocal micrographs of the (a) weak, (b) medium and (c) strong isotropic texture.

3. Results

3.1. Iso-textured wafers: determining the characteristic angle

The respective characteristic angles ω_c (63°, 60°, 49°) of the spherical-cap texture (see Fig. 1a) are chosen such that the corresponding simulated reflectance matches the measured front reflectance of the textured wafers. In addition, the reflectance of the samples with planar surface and with random pyramid texture are shown for comparison (see Fig. 3a). The reflectance and corresponding ω_c agree with literature [5, 6] and with simulations done with OPAL 2 [14] (see Fig. 3b).

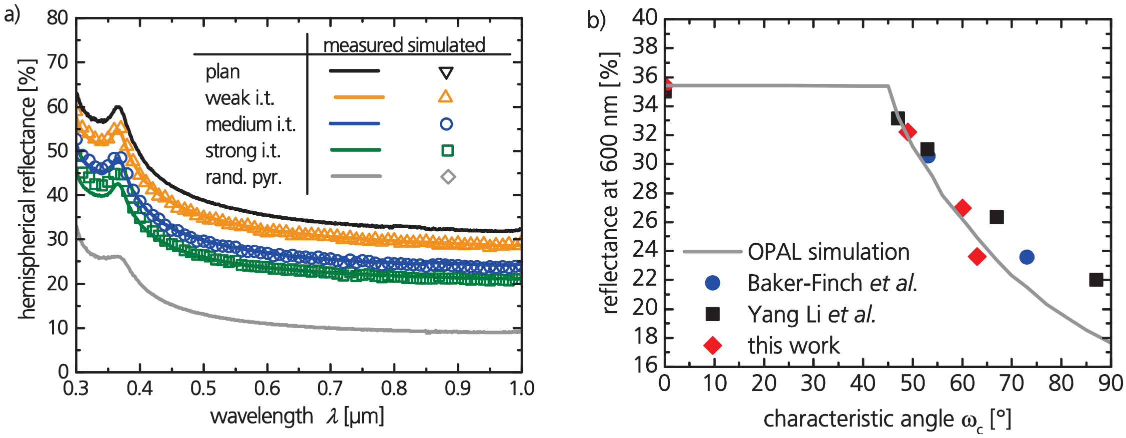

Fig. 3. (a) The measured and simulated spectral reflectance of all surface textures match closely. (b) Reflectance at a wavelength of 600 nm and corresponding characteristic angles from the literature and from OPAL 2 [14] simulations.

3.2. Iso-textured cells: analyzing texture and light trapping properties

For the optical simulation of the cells, the geometry of the texture, in particular ω_c is chosen as for the wafers. The refractive index of the SiN_x anti-reflection coating (ARC) is determined from the planar sample using spectral ellipsometry. We chose the thickness of the ARC to match the measured reflectance for $\lambda < 900$ nm, which coincides with ellipsometric measurements. The optical properties of the thin ARC are modelled using the transfer matrix method, based on Fresnel's equations. In the silicon bulk, ray optics are combined with the Lambert-Beer law to describe the attenuation of the light intensity. In order to match the measured reflectance of the cells with Al-BSF above $\lambda > 900$ nm, the empirical Phong model is assigned to the flat rear surface. The Phong parameters $R_0 = 0.7$ and $\omega_P = 4$ are chosen to mimic the optics including light scattering and reflected intensity of a full-area Al-BSF [15]. The PERC rear surface is simulated applying the tilted-mirrors approach [11, 12], which describes light scattering at the rear surface by including the actual rear surface morphology explicitly into the CAD model (see Fig. 1b). The implemented rear surface morphology corresponds to a single-sided etched-back surface of textured mc-Si wafers (6 µm etch-back) [16] and was measured using a confocal microscope. Within the titled-mirrors approach, the amplitude of the light reflected at the rear surface is calculated again using the transfer matrix formalism and assuming 10 nm AlO_x covered by 100 nm SiN_x and a thick aluminum layer. Lacking refractive index data of screen-printed aluminum, the refractive index of elementary aluminum is applied, corresponding to physical vapor deposited (PVD) aluminum. In the simulations, the front metallization is not taken into account. Since the reflectance is measured at finished solar cells including front metallization, the reflectance of the screen-printed front metal is subtracted from the measured reflectance in order to compare measurement and simulation directly. Since silver significantly absorbs light, particularly below 400 nm, this has been taken into account for the front metallization using the data for screen-printed silver from Thaidigsmann *et al.* [17].

Table 1. Parameters of the surface textures and cells with 79 nm ARC thickness and Al-BSF rear side.

Texture type	RMS-roughness (μm)	Surface enlargement factor	R(0.6µm, wafer) (%)	ω_C (°)	J_{ph} (cell) (mA/cm^2)	J_{ph} (module) (mA/cm^2)
Strong iso-texture	1.18	1.57	23.6	63	39.1	37.8
Medium iso-texture	1.04	1.48	26.9	60	38.6	37.9
Weak iso-texture	0.86	1.17	32.2	49	37.9	37.3

The measured reflectance of the mc-Si solar cell can be modelled accurately in the relevant spectral range from 300 nm to 1200 nm (see Fig. 4). The calculated generation currents of the solar cells with Al-BSF and PERC rear side are shown in Fig. 6.

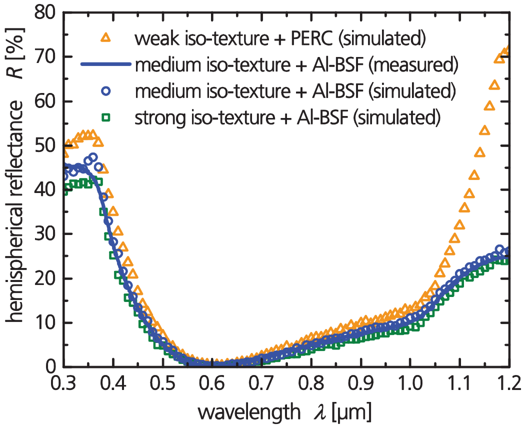

Fig. 4. Measured and simulated spectral hemispherical reflectance of silicon solar cells with strong, medium and weak iso-textures, 70 nm thick ARC, and with full-area Al-BSF and PERC rear side. The front metallization is excluded.

3.3. Encapsulated cells: quantifying direct cell-to-module losses

Encapsulated cells are simulated like the bare cells, but assuming an ARC thickness of 79 nm, covered by 450 µm EVA and 3 mm glass. The metallization and indirect coupling of light scattered at the front metallization and at the back-sheet are excluded in the simulation. The measured reflectance of the encapsulated cell including front metallization is shown in Fig. 5 along with the simulated reflectance of the medium iso-texture with Al-BSF rear side and the simulated reflectance of the weak iso-texture with PERC rear side. Between 300 nm and 1000 nm, all three curves are very similar: The measured reflectance is 1-2$\%_{abs}$ higher than the corresponding simulation, probably due to neglecting the front metallization in the simulation. The simulated reflectance of the weak iso-texture is only 0-1$\%_{abs}$ higher than that of the medium iso-texture because the reflection is dominated by the air-glass interface. Above 1000 nm, the larger escape light of the PERC cell compared to the Al-BSF cell due to higher internal reflection of the PERC cell is also apparent in the reflectance on module level.

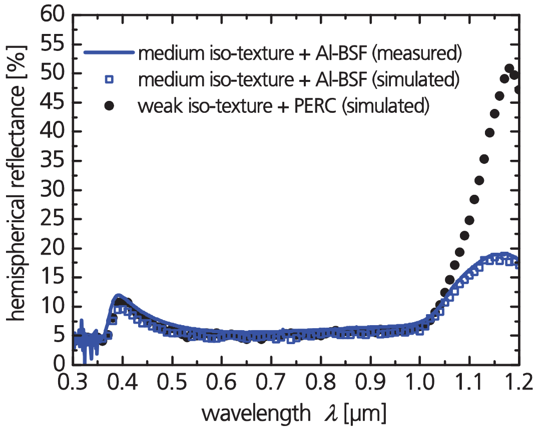

Fig. 5 Measured and simulated reflectance of encapsulated iso-textured cells with Al-BSF and PERC rear surface reflection.

The encapsulated iso-textured cell (medium iso-texture) with Al-BSF exhibit a j_{ph} which is only 1.2 mA/cm² smaller than the j_{ph} for the PERC rear side (Fig. 6), whereas this difference is larger (1.7 mA/cm²) for the bare cells. The cell-to-module loss of the generation current density j_{ph} is 0.7 mA/cm² for the Al-BSF cell and 1.2 mA/cm² for the PERC cell.

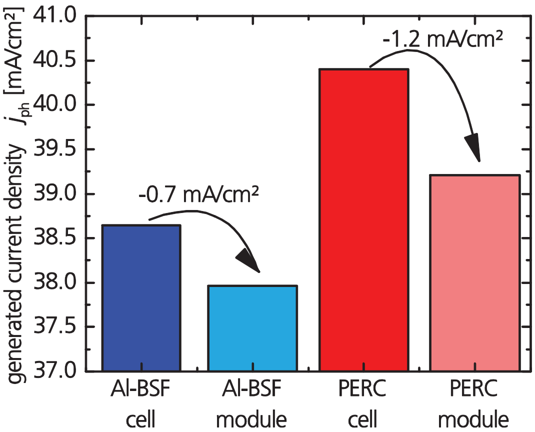

Fig. 6. Simulation of the generated current densities j_{ph} under 1 sun illumination for bare and encapsulated cells with the medium iso-texture and 79 nm ARC thickness.

4. Discussion

As symmetry element for the iso-texture, the spherical-caps approach is chosen. This constitutes a simplification, since the micrographs (Fig. 2) show that the cavities are not all equally large and show a longish shape.

Furthermore, the wafer surface cannot be covered to 100% with spherical caps with circular base for geometrical reasons. Nevertheless, the results of the present work show that the reflectance of wafers, cells and modules can be modelled with this approach. The literature shows that even the angular distribution of the reflected light of iso-textured wafers can be described [6].

The reflection of the metallization and scattering of light from the back sheet on the active cell is neglected. Since the interaction of the metallization and the back-sheet scattering with the surface texture of the cell is a second order effect, both the reflection of the metallization and the back-sheet scattering are largely independent of the surface texture. Therefore, the results remain valid qualitatively and largely quantitatively.

5. Conclusion

The spherical-caps geometry is successfully applied to model the reflection of iso-textured mc-Si wafers and cells in the complete relevant spectral range including light trapping and escape light, as shown by the good correlation between simulated and measured reflectance data. The cell-to-module (CTM) loss of mc-Si cells with Al-BSF is smaller than that of mc-Si cells with passivated rear side. This fact is quantified in terms of charge carrier generation rate CTM loss to 0.7 mA/cm² (Al-BSF) and 1.2 mA/cm² (passivated). Nevertheless, encapsulated cells with passivated rear are expected to show a higher generation rate (+1.2 mA/cm²) than those with Al-BSF rear side.

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References

[1] Y.M. Yang, A. Yu, B. Hsu, W.C. Hsu, A. Yang, C.W. Lan, Development of high-performance multicrystalline silicon for photovoltaic industry, Progr. Photovolt., (2013) to be published.
[2] S.P. Group, International Technology Roadmap for Photovoltaic, in, March, 2014.
[3] A. Hauser, I. Melnyk, P. Fath, S. Narayanan, S. Roberts, T.M. Bruton, A simplified process for isotropic texturing of mc-Si, in: Proceedings of 3rd World Conference on Photovoltaic Energy Conversion, 2003, pp. 1447-1450.
[4] R. Einhaus, E. Vazsonyi, J. Szlufcik, J. Nijs, R. Mertens, Isotropic texturing of multicrystalline silicon wafers with acidic texturing solutions, in: Proc. 26th IEEE PVSC, Anaheim, California, USA, 1997, pp. 167-170.
[5] Y. Li, Z. Li, Y. Zhao, A. Lennon, Modelling of light trapping in acidic-textured multicrystalline silicon wafers, International Journal of Photoenergy, 2012 (2012).
[6] S.C. Baker-Finch, K.R. McIntosh, M.L. Terry, Isotextured silicon solar cell analysis and modeling 1: optics, IEEE Journal of Photovoltaics, 2 (2012) 457-464.
[7] A. Ingenito, O. Isabella, S. Solntsev, M. Zeman, Accurate opto-electrical modeling of multi-crystalline silicon wafer-based solar cells, Sol. Ener. Mater. Sol. Cells, 123 (2014) 17-29.
[8] I.M. Peters, Y.S. Khoo, T.M. Walsh, Detailed current loss analysis for a PV module made with textured multicrystalline silicon wafer solar cells, IEEE Journal of Photovoltaics, 4 (2014) 585-593.
[9] Sentaurus TCAD, Technology computer aided design (TCAD), in, Synopsys, Zürich, Switzerland.
[10] B.T. Phong, Illumination for computer generated pictures, Communications of the Association for Computer Machinery, 18 (1975) 311-317.
[11] J. Greulich, N. Wöhrle, M. Glatthaar, S. Rein, Optical modeling of the rear surface roughness of passivated silicon solar cells, Energy Procedia, 27 (2012) 234-239.
[12] N. Wöhrle, J. Greulich, C. Schwab, M. Glatthaar, S. Rein, A predictive optical simulation model for the rear-surface roughness of passivated silicon solar cells, IEEE Journal of Photovoltaics, 3 (2013) 175-182.
[13] D. Biro, U. Belledin, A. Weil, M. Zimmer, A. Grohe, S. Rein, J. Rentsch, R. Preu, PV-Tec: retrospection to the three years of operation of a production oriented research platform, in: Proc. 24th EU PVSEC, Hamburg, Germany, 2009, pp. 1901-1905.
[14] K.R. McIntosh, S.C. Baker-Finch, OPAL 2: Rapid optical simulation of silicon solar cells, in: Proceedings of the 38th IEEE Photovoltaic Specialists Conference, Austin, TX, USA, 2012, pp. 000265-000271.
[15] M. Rüdiger, C. Schmiga, M. Rauer, M. Hermle, S.W. Glunz, Efficiency potential of n-type silicon solar cells with aluminum-doped rear p+ emitter, IEEE Trans. Electron Devices, 59 (2012) 1295-1303.
[16] M. Richter, M. Zimmer, J. Rentsch, Y. Friedekind, A. Fischer, Characterization of the rear surface roughness of wet chemical polished industrial-type solar cells, in: Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th, IEEE, 2014, pp. 1238-1243.
[17] B. Thaidigsmann, A. Wolf, D. Biro, Accurate determination of the IQE of screen printed silicon solar cells by accounting for the finite reflectance of metal contacts, in: Proc. 24th EU PVSEC, Hamburg, Germany, 2009, pp. 2056-2059.