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Angle-dependent ray tracing simulations of reflections on pyramidal textures for silicon solar cells

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Abstract

Pyramidal textures are commonly used to reduce reflections from silicon solar cells and improve light absorption by light trapping. They are generally modelled or characterised under normal incidence. In this work, a monolayer 3D ray tracing program taking into account the polarisation of light have been developed, validated and used to compute the directional-hemispherical reflectance versus the azimuth and incidence angles for both regular upright pyramids and inverted ones, with (111) facets. Results are given for a wavelength of 0.7 μm. They show that this reflectance is not minimal at normal incidence but for an incidence angle near 20° and that upright pyramids can have a lower hemispherical reflectance than inverted ones for incidence angles in the middle range. The bihemispherical reflectance is 19.6% for regular upright pyramids and 20.7% for inverted ones. The effect of the pyramids aspect ratio on the hemispherical reflectance at normal incidence is also studied. This reflectance decreases with the aspect ratio of both textures. Above an aspect ratio of 0.51, inverted pyramids have a lower hemispherical reflectance. But their bihemispherical reflectance is lower only for aspect ratios below 0.23.

Keywords: Texture; Ray tracing; Reflectance; Solar cell

1. Introduction

Surface texturing is commonly used to reduce reflections from silicon solar cells and improve light absorption by light trapping (Razykov et al., 2011). In particular, the record monocrystalline silicon cell (25% efficiency) has an inverted pyramid surface texture (Zhao et al., 1998; Green et al., 2013). Pyramidal textures are typically produced by etching (100)-oriented monocrystalline wafers in an alkaline solution such as KOH or NaOH (Moreno et al., 2014). The etching being anisotropic gives theoretically (Baker-Finch and McIntosh, 2013) square-based pyramids with (111) facets inclined by 54.74° from the horizontal plane.

The efficiency of surface textures is generally evaluated by characterising or modelling under normally incident light, and it is well known that in those conditions inverted pyramids have a lower reflectance than upright ones (Baker-Finch and McIntosh, 2011). Sometimes the zenith incidence angle is considered (Rodríguez et al., 1997; Yu et al., 2003; Byun et al., 2012; McIntosh and Baker-Finch, 2012), but we found very few studies considering

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both zenith and azimuth incidence angles (Parretta et al., 1999; Gjessing et al., 2011). In this paper, we study the directional-hemispherical reflectance of regular upright and inverted pyramids, taking into account both angles, and their bihemispherical reflectance (i.e. hemispherical-hemispherical reflectance, the first adjective relating to the collimation of the source, the second of the detector (Nicodemus et al., 1977; Hapke, 2012)).

First, the development and the validation of a 3D ray tracing model taking into account polarisation are presented. It is then used to compute and study the directional-hemispherical reflectance of regular upright and inverted pyramids versus zenith and azimuth angles. Then we compare these two textures under diffuse light by computing their bihemispherical reflectance.

Although chemical etching is imposing the base angle of pyramids, it could be interesting to obtain pyramids with a higher base angle in order to reduce reflections and to increase light trapping (Hua et al., 2010). We therefore in a second part study the effect of the aspect ratio of both types of pyramids on their directional-hemispherical and bihemispherical reflectances.

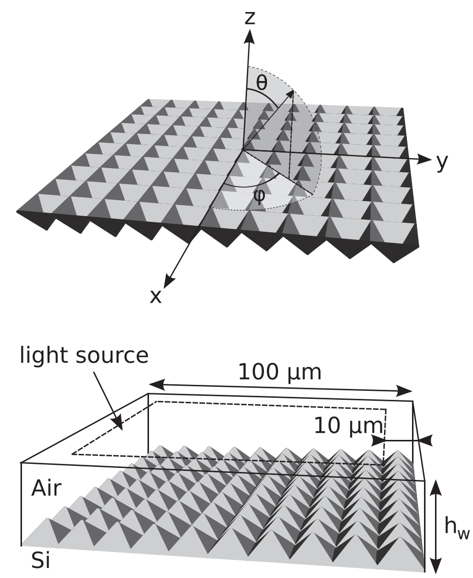

Fig. 1. Three-dimensional model of textured surfaces: regular inverted pyramids (top) and upright pyramids (bottom). In the model, the direction of a light ray is defined by the polar angle θ and the azimuth angle ϕ. The incidence angle is therefore π–θ. The altitude of the light source is not to scale, being in fact 0.1 µm above pyramids.

2. Simulation

2.1. Model description

A ray tracing program was developed in Fortran using the test driven development methodology (Gagliardi, 2007), which is well adapted to scientific computing programs: for each needed function, automated tests are first written. Then the function is written, with the simplest possible code that can pass the tests. Then the code is refactored or optimised if needed, and the tests launched. The development process continues with another function. The automated tests allow the developer to code with more confidence. System tests can be added when the model is functional, in order to avoid any regression in the code. Following this methodology, we gradually developed a 2D model, then a 3D one, and finally we introduced a rigorous approach of the polarisation of light.

Indeed, a 3D model is necessary to study a texture illuminated under any incidence angle and azimuth angle, and the polarisation must be taken into account to study inverted pyramids because reflections on orthogonal facets produce polarisation rotations (Trupke et al., 2006; Baker-Finch and McIntosh, 2011). Our model can simulate any surface that can be mathematically described as a $z = f(x, y)$ continuous function. This surface must be meshed with triangles: in the case of a square-based pyramids texture, each pyramid is simply meshed with four triangles (Fig. 1). These pyramids have a height or depth of 7.07 µm, their facets being inclined by 54.74° from the horizontal plane, although recent studies have confirmed that in practice that angle can be slightly lower (Yang et al., 2013; Baker-Finch and McIntosh, 2013), a point that will be discussed later. The dimensions of the pyramids being much greater than the wavelengths absorbed by silicon, the geometric optics approximation can be considered valid. Under this hypothesis, the optical behaviour does not depend on the width of the pyramids but only on the inclination angle of their facets (Byun et al., 2011; Lien et al., 2012).

Each ray direction is defined using spherical coordinates as shown in Fig. 1. Light is considered unpolarised: each launched ray has its own complex electric field vector, orthogonal to the propagation direction (the medium is considered linear and isotropic), oriented in space using a random angle in the 0–2π range and defined as a unit vector. The reflected electric field vector is computed using the three-by-three polarisation ray tracing matrix as extensively described by Yun et al. (2011) and resumed by Baker-Finch and McIntosh (2011). This matrix is the product of three matrices: a first orthogonal matrix to transform between the global coordinate basis and the local s–p coordinates, the reflection Jones matrix and a third orthogonal matrix to transform between the local s–p coordinates and the global coordinate basis. The Jones Matrix includes the complex amplitude Fresnel coefficients computed for s and p polarisations (Hapke, 2012). These coefficients are calculated using the incidence angle and the complex optical indexes of air (Ciddor, 1996) and silicon (Green, 2008) at the considered wavelength, air being the only medium above silicon. The $\cos(\theta_i)$ geometric factor of the solar energy actually captured under an incidence angle θ_i is omitted to better compare the actual light-trapping efficiency of the textures at various azimuth and incidence angles (Gjessing et al., 2011).

To compute the hemispherical reflectance at incidence angles below 70°, the computing window area is