Wavelength and angle resolved reflectance measurements of pyramidal textures for crystalline silicon photovoltaics

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Abstract
Wavelength and angle resolved scattering (WARS) reflectance measurements are attractive to the photovoltaic (PV) industry as a means of characterizing the light-trapping properties of a textured front surface. Moreover, at the PV module level, where a stack comprising encapsulants and glass is present, large angle scattering can promote total internal reflection at the interfaces and redirect light back towards the solar cell, thus increasing the photocurrent of the device. In this work, we present WARS measurements of a potassium hydroxide (KOH)etched random pyramid surface in the $\theta = 6^\circ$–$90^\circ$ range and identify the main paths the photons experience through reflections from various facets of the pyramids. Our results, combined with ray-tracing predictions, show that a reassessment of the morphology for simulation inputs is advised for a more comprehensive description of the experimental light paths due to a distribution of power across multiple scattering angles and a lower average pyramid base angle. In addition, we discuss the implications on the total amount of light trapped at the glass-air interface and show that for a typical encapsulant refractive index of 1.5, approximately 14.5% of the scattered light is predicted to be trapped by the fabricated pyramidal texture. This is a significant increase over the 3.8% calculated to be trapped when assuming a dihedral base angle fixed to 54.74°.

KEYWORDS
antireflection, light trapping, optics, scattering, texture

1 | INTRODUCTION

Photo-generation inside the substrate of a silicon solar cell can be enhanced by addressing the optical losses associated with top surface reflectance and poor absorption of low energy photons inside the bulk.1,2 Micron-scale texturing combined with a thin film antireflection coating is the crystalline silicon photovoltaics (PV) industry standard for addressing these losses. Texturing is achieved through either an acidic etching process for multicrystalline silicon or an alkaline etching process, based on KOH or tetramethylammonium hydroxide (TMAH), for mono-crystalline silicon.3 The latter results in randomly distributed, upright, micron-sized pyramids with a theoretical base angle of 54.74° corresponding to the dihedral angle between the (100) surface of the wafer and the slower etching {111} crystallographic planes. Light reflected from a flat silicon surface is directed away from the cell; however, light reflected from an inclined facet of a pyramid may...
be redirected onto an adjacent facet, providing additional interactions of light with the cell surface and thereby increasing the overall amount of light coupled into the cell. In combination with an approximately 80-nm SiN\textsubscript{x} anti-reflective coating (ARC), this reduces the surface reflectance to below 10% in the 300–1100 nm wavelength range.\textsuperscript{4,5} Improving the optical path length through scattering of light to higher angles as it is coupled into the silicon leads to more absorption of light for a fixed substrate thickness.\textsuperscript{6–8} Alternatively, the thickness of the substrate can be reduced while maintaining the amount of light absorbed, reducing the amount of material required in the device and therefore the cost.\textsuperscript{9} Furthermore, when encapsulated to form a PV module, additional interfaces are created between the solar cell and the surrounding environment. Total internal reflection (TIR) can occur if the light is scattered by the silicon surface so that it is incident at an angle greater than the critical angle at these interfaces. This mechanism will cause light to be redirected back onto the cell, increasing the overall amount that is coupled into the device.\textsuperscript{5,10,11} Characterizing the wavelength and angular scattering profile of solar cell surfaces can therefore help to quantify the light trapping properties of various textures that complement their antireflective properties.

Diffuse reflectance can be measured using an integrating sphere by eliminating the specular reflection, and thus, the reflectance haze can be calculated as a means of quantifying the percentage of the total light scattered from a surface.\textsuperscript{12} However, this provides no information on the angular distribution of scattered light, a key consideration when determining the proportion that will undergo TIR at the glass-air interface. Few setups and methods have been proposed so far to capture such dependencies.\textsuperscript{7,10,11,13–17} Baker-Finch and McIntosh\textsuperscript{11} reported scattering measurements on random pyramid textures that showed the peak in the scattering angle is much lower than that predicted from ray-tracing on \{111\} facetted pyramids of characteristic dihedral angle 54.74\textdegree. Yang et al.\textsuperscript{10} presented angle resolved reflectance measurements of pyramid textured surfaces for a single wavelength by capturing the reflection on photographic paper. Similarly, they found a peak in the scattered reflections at angles much lower than those predicted by simulations. This supports reports\textsuperscript{5,18,19} that the characteristic angle of most random pyramid textured surfaces is less than 54.74\textdegree and means that the proportion of reflected light trapped at the air-glass interface and redirected back onto an encapsulated cell will be reduced. More recently, Fung et al.\textsuperscript{20} presented a solution to improve the ray tracing simulations of random pyramidal textures using Phong scattering implemented into the Monte Carlo simulations. Using a defined dihedral base angle of 51\textdegree, the group successfully replicated the experimental results obtained by Yang at an incident wavelength of 532 nm. In the study, the addition of Phong scattering mimics the base angle distribution commonly observed in morphological characterization of fabricated pyramidal textures. Moreover, higher photon paths corresponding to angles above 70\textdegree have been simulated that could not be matched to any experimental data available in literature so far.

In this work, wavelength and angle resolved scattering (WARS) measurements on a monocrystalline silicon sample textured with KOH etching to form random upright pyramids are presented and analyzed. Firstly, a comprehensive description is provided of the different paths the light can experience when incident on pyramid textures with characteristic angles of 54.74\textdegree, with the exit direction reported as polar scattering and azimuth angles. Then, hemispherical reflectance measurements and WARS measurements of a KOH etched sample are presented, the latter showing poor agreement to the theoretical predictions. An updated morphological description of the light paths is then presented, which shows good agreement to WARS results. The impact of azimuthal rotation on the WARS results is also presented, along with a discussion of the fraction trapped by TIR at the glass-air interface in an encapsulated texture.

## 2 | THEORETICAL BACKGROUND

The interaction of photons with micron-scale pyramids is theoretically well understood and can be simulated using geometric ray tracing to obtain angular information on the surface reflections, as the wavelengths of the incident photons are well below the feature size.\textsuperscript{5–7,21} Light can experience up to seven distinct paths upon interaction with the \{111\} facets.\textsuperscript{5,21} These paths present different reflectance weightings and each result in rays that exit in a direction that can be defined by a polar scattering angle and an azimuth angle. In this work, a custom Matlab script was used to define the vector of the incident light, as well as the pyramidal plane normals, for calculations of both the polar and azimuth exit angles for different photon paths. The results are summarized in Table 1, with the polar scattering angles

| Table 1 | Calculated polar and azimuth exit angles for photon Paths A–G for pyramids with base angle of 54.74\textdegree |
|---------|----------------------------------|
| Path    | Reflection angle (\textdegree) < plane number > (see Figure 1A) | Polar scattering angle \( \theta \) (\textdegree) | Azimuth angle \( \phi \) (\textdegree) |
| A       | 54.74 <1> | 15.78 <2> | 38.96 | 0 |
| B       | 54.74 <1> | 15.78 <2> | 86.3 <1> | 31.56 | 0 |
| C       | 54.74 <1> | 78.9 <3> | 29.48 <2> | 31.6 | 36.86 |
| D       | 54.74 <1> | 78.9 <3> | 71.28 <4> | 74.97 | 12.53 |
| E       | 54.74 <1> | 78.9 <3> | 71.28 <4> | 88.76 <3> | 73.49 | 10.48 |
| F       | 54.74 <1> | 78.9 <3> | 71.28 <4> | 51.67 <2> | 12.76 | 18.44 |
| G       | 54.74 <1> | 78.9 <3> | 71.28 <4> | 88.76 <3> | 52.71 <2> | 10.4 | 14.91 |

[Correction added on 8 October 2020, after first online publication: the placement of data in this table has been corrected in this version of the article.]
matching with other reports,4,21 for a fixed characteristic dihedral angle of 54.74° and incident light normal to the silicon substrate. The calculations reveal that Paths C–G exhibit off-axis (azimuth) exit angles. The table shows on which plane the reflections occur for each path, as well as the incident angle on that respective plane relative to the normal to the plane.

Figure 1A) shows a schematic of four intersecting [111] planes on a pyramidal textured surface, viewed from above with the plane numbers from Table 1 indicated. Previous ray-tracing studies have shown that Path A represents approximately 68% of the total reflected power.4,21 This path consists of a double reflection on the facets of the pyramids (Plane 1 and then Plane 2), and then an exit from the pyramidal array at an angle of 4°–180°, where α is the dihedral base angle of the structures,10,11,17,21 as shown in Figure 1B). This corresponds to a scattering angle of 38.96° when α = 54.74°. Therefore, at 0° azimuth angle, it is expected that most of the measured reflected signal of the pyramid texture is at approximately 39° (corresponding to Path A), and a smaller peak at approximately 32° (corresponding to Path B). No other distinct features at other scattering angles within the 0°–azimuth plane should be present due to the fixed geometry of the structures. Figure 1C) shows a schematic of the TIR mechanism at the glass-air interface in an encapsulated PV module with pyramidal front surface. The fraction of scattered light trapped at this interface can be calculated for various encapsulants based on their refractive index and used as a complementary metric for assessing and comparing textured surfaces employed in silicon solar cells (see Section 4).

3 | EXPERIMENTAL METHODS

3.1 | Sample fabrication

N-type CZ <100> 1–5 Ω cm c-Si wafers were cleaved into 4 × 4 cm² pieces and then cleaned using a 3:1 H₂SO₄:H₂O₂ piranha solution. This was followed by a thorough de-ionised water rinse and then a 5-min dip into a 7:1 H₂O:H₂SO₄ solution for native silicon dioxide removal. The alkaline etching of the micron-scale pyramids was carried out in a 0.2-M KOH and 5% isopropyl alcohol (IPA) mixed solution heated at 80 °C for 60 min14 and followed by a rinse in de-ionised water.

3.2 | Characterization

Morphological characterization of the textures was carried out using scanning electron microscopy (SEM, Carl Zeiss NVision40) at an accelerating voltage of 2 kV and with an aperture of 120 µm. Cross-sections through the pyramid structures were prepared by milling using the Ga-focused ion beam (FIB) capability in the Zeiss NVision40 FIBSEM. This involved milling of the cleaved cross-sectional surface back to the center of a pyramid (using progressively smaller FIB beam currents from 13 nA to 80 pA) and then capture of an SEM image of the cross-section. The SEM image was processed to correct for the tilt angle of the stage relative to the pyramid facet normal, and then, the pyramid base angles were measured on the image.

Hemispherical reflectance was measured with a DTR6 integrating sphere as part of a Bentham PVE 300 system in the 300–1100 nm wavelength range, at an angle of incidence of 8° and using a 2% Labsphere diffuse reflective standard (SRS-02-010). For diffuse reflectance measurements, one of the ports of the integrating sphere was replaced with a light trap to remove the specular component of the reflected beam (i.e., light reflected into the angular range ±6° about the angle of specular reflection).

The WARS measurements were taken using a custom-built broadband angle-resolved optical spectrometer setup, described in Payne et al.15 and adapted for reflectance measurements. The white super continuum laser source (Fianium SC450-222) outputs light in the 450–2000 nm wavelength range with a beam spot size of approximately 1.5 mm. The data are collected using a 600-µm core multimode optical fiber mounted on the detector arm and transmitted to a Glacier X spectrophotometer with 25-µm wide slits, sensitive in the 350–950 nm wavelength range. Motorized rotation stages are used to provide precise control over the intensity of the laser (by using two cross-polarizers), the polarization of the light, the angle of incidence, the azimuth angle of the sample, and the position of the

![Figure 1](image-url)  **FIGURE 1** (A) Planes of the pyramids as viewed from above, numbers indicated as in Table 1; (B) schematic of light experiencing a double reflection, then exiting from the array, that is, tracing out Path A; (C) schematic of total internal reflection (TIR) in an encapsulated module, showing redirection of light towards bulk if outside the escape cone. Layers not to scale [Colour figure can be viewed at wileyonlinelibrary.com]
detector. The collection arm is aligned to the center of rotation of the sample on both the polar and azimuth axes and to the laser beam path. For this study, the textured sample was illuminated at normal incidence (0°) and the detector is swept around the sample in an arc from 6° to 90° as depicted in Figure 2. The WARS measurements were carried only with p-polarized light incident on the sample. More complete data can be obtained by averaging signals arising from both s and p polarization. However, it is expected that minimal changes would occur in the collected data when the polarization is changed under normal incidence.

The collected data were normalized with respect to the direct beam measurement of the laser source and then geometrically corrected as in Equation 1 to account for the in-plane movement of the detector, which captures a smaller amount of the total light scattered at large angles. Here, a is the distance between the detector and the sample (~15 cm), θ is the polar scattering angle, and R is the radius of the detector aperture (~600 μm).

\[
I_{\text{scattered}}(\theta, \lambda) = \frac{I_{\text{measured}}(\theta, \lambda)}{\frac{4 \pi}{\sin(\theta)}}.
\] (1)

The integration time of the spectrometer is assumed to scale linearly to the spectrometer counts in the detected signal and is chosen such that the signal to noise ratio of the data is maximized. Data are collected for every 1° movement of the detector. In addition, for azimuth rotations of the texture, data are collected for every 5° azimuth. The angular resolution of the system is ±0.4°, which is sufficient to prevent overlapping of the data in consecutive measurements.

4 | RESULTS

4.1 | Morphology

Figure 3 shows SEM images of the resulting pyramidal surface, which present randomly distributed upright structures of varying feature size. Figure 3A) is a top-view SEM image of the pyramids, showing that they overlap to entirely cover the area and have base widths within the range of approximately 5–25 μm. Figure 3B) is an SEM image of the pyramidal layer taken at a 54° stage tilt, showing overlapping pyramids with well-defined, smooth facets.

4.2 | Hemispherical reflectance and haze

The total hemispherical reflectance spectrum, measured from the pyramidal textured surface is shown in Figure 4 as a solid black line, along with the diffuse hemispherical reflectance spectrum shown as a
dashed line. The reflectance haze spectrum, defined as the ratio between the diffuse and the total hemispherical reflectance, is shown as a red line, corresponding to the right-hand y-axis. The pyramid sample has a specular reflectance, which is less than 10% of the total reflectance, and is shown to scatter the majority of reflected light to angles larger than 6°. The weighted average haze value for this texture is 0.92. However, haze measurements do not provide information on the angular distribution of scattered light, which is key in determining how much can be trapped by TIR at the glass-air interface. As such, the WARS measurements presented in the following sections are required for a more comprehensive optical characterization of light trapping textures.

4.3 | WARS

A WARS measurement of the random pyramid sample, with p-polarized light incident normal to the sample surface, is presented in Figure 5. The largest signal across the wavelength range occurs at approximately 28°, which is contrary to the 39° calculated in Table 1. However, the WARS result is in good agreement with Yang et al.,10 who found a similar scattering angle distribution for pyramidal textures at a single wavelength of 532 nm. These findings are indicative of a different pyramidal morphology with, as Baker-Finch and McIntosh have also reported, dihedral base angles (α) formed by a random pyramid etch being significantly less than the 54.74° expected from theory.18 Moreover, the stronger signal attributed to the shorter wavelengths matches well to the hemispherical reflectance measurements. Even though no measured data are expected at large polar scattering angles, the small signal in this region of the measured data is indicative of higher photon paths emerging on-axis. The 28° maximum polar scattering angle observed in the data corresponds to \( \alpha \approx 52° \), which is within the range of 49° to 53° reported by Baker-Finch et al. and others.4,5,18,19

Alkaline etching of silicon results in much faster etching of {100} planes compared with {111} planes, leading to well-defined random pyramids. However, it has been previously reported that the etch rate of {111} planes is nonzero and an effect on the dihedral base angle of the pyramids is therefore observed. Green23 has proposed that the base angle becomes \( \alpha = 54.74° - \arctan(r) \), where \( r \) is the ratio of the etch rates of [111] planes to [100] planes. In practice, the value of \( r \) is not zero, and it depends on the amount of IPA added to the alkaline solution, as well as surface activators and temperature.24,25 It commonly takes values between 0.05 and 0.2,25 with an accepted average value of 0.1,23,26 which explains the base angle decrease by up to 6° normally observed in fabricated samples. Baker-Finch and McIntosh11 later proposed a reduction in base angle based on \( \alpha = 54.74° - \arctan(\sqrt{2/3}r) \) to be a better approximation.

To confirm this hypothesis, a milling procedure was performed on a pyramid, perpendicular to the silicon substrate and close to the apex of the structure to enable a direct measurement of dihedral base angle, as shown in Figure 6A. By viewing the milled pyramid facet at a stage tilt of 54° and applying tilt correction to the image to correct for the difference between viewing angle and the milled facet angle, direct measurements of \( \alpha \) can be taken, as shown in Figure 6B. Six angles were measured (three on each side of the milled facet) giving an average value of 52.1° with a standard deviation of 1.1°, in good agreement with previous reports.5,11,17,23–25

These findings show that a re-evaluation of the morphology of the alkaline-etched pyramids is necessary, along with updated descriptions of the pathways the photons experience. Table 2 shows the exit angles at each of the Paths A–G for a pyramid texture with an average

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**FIGURE 5** Wavelength and angle resolved reflectance measurement of the pyramid texture, intensity indicated in color (a.u.). Highest signal recorded at 28° agrees with previous reports [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 6** (A) Top-view scanning electron microscopy image after milling through a pyramid perpendicular to the silicon substrate; (B) base angle measurement for the milled pyramid, stage tilted to 54°, and tilt correction to 36° so that vertical measurements on the cross-sectional surface are correct


**TABLE 2** Calculated angle ranges for Paths A–G for pyramids with experimental measured base angles of 51°–53.2°. Paths B, E, and G are no longer allowed for this new dihedral base angle range. The calculated relative intensities of these disallowed paths, taken from other studies, are presented in Figure 7. The vertical dashed lines indicate the peak base angle 52.1° ± 1.1°. The decrease in α reduces the number of possible paths to only four. The reflectance weightings of Paths B, E, and G (visible only for higher base angles) are redistributed amongst Paths A, C, D, and F. For Paths B, E, and G, the calculations result in a predicted incident angle greater than 90° on one of the facets (i.e., the facet is missed and that path is no longer possible). As such, Path B now becomes Path A, and Paths E and G become Path D. Using previously reported data, the proportion of light in the remaining paths can therefore be approximated (see Table 2, Column 6). The results in Table 2 give a more accurate description of the distribution of light scattered from fabricated random upright pyramids textures compared with the calculation results in Table 1.

In order to verify the angle ranges from Table 2, the measured data at 0° azimuth were integrated over the entire wavelength range and are presented in Figure 7. The vertical dashed lines indicate the upper and lower limits of the calculated ranges. Although the upper limit in the measured signal is in line with the calculations, the predicted lower limit is overestimated as the signal begins to rise at lower angles. This is indicative of pyramids with dihedral base angles below 51°, possibly as low as 49°, within the sample. The FIBSEM measurements were limited to two facets, so it is entirely possible that lower base angles exist in the sample. Atomic force microscopy (AFM) measurements from other groups on pyramidal textured surfaces support this, suggesting a peak base angle of 49°–50° with a wide distribution. Some variation in peak base angle is expected as it will depend on the exact etch recipe and conditions employed for any particular sample.

**4.3.1 Impact of azimuthal rotations**

Measurements at other azimuth rotations for this texture are relevant for observing other photon paths that could travel in a direction away from the horizontal plane (see Table 2). Therefore, measurements were carried out every 5° azimuth rotation in the 0°–90° azimuth range. The intensity, integrated over the wavelength range, is plotted in Figure 8A as a function of polar scattering angle for azimuth rotations of 0°–40°. The peak in intensity is seen to decrease and shift to lower angles as the azimuth angle increases, which corresponds to the exiting light from the dominant Path A moving further away from the detector in the horizontal plane and the lower intensity Path C light moving into the horizontal plane. Vertical dashed lines are traced through the positions of the peaks for 0° and 40° azimuth and mark polar scattering angles that lie in the calculated ranges for Paths A and C, respectively (see Table 2). Figure 8A also shows that there are some smaller peaks present at large polar scattering angles that emerge close to the predicted range of Path D (i.e., 76°–79°). These signals are in good agreement to the results of Fung et al., where the addition of Phong scattering in the ray tracing model leads to small peaks at polar angles around 80° that have not been experimentally measured until now.

Figure 8B shows the intensity, integrated over the wavelength range and polar scattering angle, as a function of azimuth rotation from 0° to 90°. The plot exhibits maxima at 0° and 90° azimuth and a minimum at 45° azimuth, as expected from the symmetry of square-based pyramids. The red dashed line mirrors the signals from 0°–45° azimuth across to the 45°–90° range. Slight differences between the mirrored and actual signals (such as 0° and 90° azimuth) can arise from different morphologies of the neighboring pyramids at the respective azimuth orientations (i.e., height, base angle, etc.). Moreover, it is evident from the SEM images presented above that facets
within the same pyramid may be slanted at different angles and not be identical. No peaks can be seen in Figure 8B) corresponding to paths other than Path A, for example there is no evidence of a peak corresponding to the Path C azimuth exit angle of $39.6^\circ - 37.9^\circ$. This is thought to be due to the large and broad peak in the integrated data corresponding to Path A masking any smaller signals that may be present from the other paths predicted in Table 2.

A comprehensive description of the surface reflections from any type of texture can be represented using polar coordinates, as shown in Figure 9 for a $0^\circ - 90^\circ$ azimuth range, Inset 1 for the entire azimuth range and Inset 2 only for scattering angles up to $40^\circ$. It should be noted that in Inset 1 of the figure, only the first quadrant corresponding to $0^\circ - 90^\circ$ azimuth shows measured data and that the other three quadrants are copied and mirrored across for a complete representation. The concentric inner circles indicate the scattering angles; the origin of the circle corresponds to a $6^\circ$ scattering angle. The strong signal at scattering angles below $30^\circ$ in Inset 1 of the figure is indicative of four-facetted pyramids and similar to the images shown in work of Yang et al., where photographic paper was used in order to capture these reflections. The tips of the square correspond to Path A.

The main finding from the WARS measurements on random pyramid textures is that the peak scattering angle is significantly lower than that predicted for $\{111\}$ facetted pyramids of characteristic angle $54.74^\circ$. This suggests that the proportion of reflected light trapped at the glass-air interface and redirected back onto an

![Figure 9](https://wileyonlinelibrary.com)

**Figure 8** Measured data integrated over wavelength range to show: (A) five increasing azimuth rotations, solid blue trace corresponding to Path A, solid black trace corresponding to Path C, and their scattering angle peak, in good agreement with results in Table 2; (B) also integrated over scattering angle to show symmetry around azimuth [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 8](https://wileyonlinelibrary.com)

**Figure 9** Measured reflection of a random pyramid texture in polar coordinates, azimuth angle range $0^\circ - 90^\circ$. Intensity shown in color (a.u.). Inset 1 shows the polar plot for the full azimuth range obtained by copying and mirroring the measured data across the other quadrants. Inset 2 shows measured data for scattering angle range $0^\circ - 40^\circ$ (magnified from the main figure) [Colour figure can be viewed at wileyonlinelibrary.com]
encapsulated cell will be much less than predicted, which motivates the need for alternative surface textures that scatter light to higher angles. These measurements can also provide insights into the texture morphology and its distribution within the sample, especially when analyzing the position and width of the largest signal corresponding to path A.

5 | FRACTION OF SCATTERED LIGHT TRAPPED

As solar cells are encapsulated to protect the substrate from moisture and damage, the measurements presented in this study can be of interest when analyzing TIR at the glass-air interface and assessing the texture’s capability to trap light and redirect it back to the solar cell. The critical angle at the encapsulant-glass interface is always lower than the critical angle at the glass-air interface; therefore, the dominant critical angle to satisfy TIR in the stack is at the virtual encapsulant-air interface, as shown in Yang et al.\textsuperscript{10} The fraction of scattered light trapped, \(f_T\), can be computed as a function of the surrounding encapsulant refractive index, as shown in Equation 2, by calculating the ratio of the reflected intensity outside the escape cone to the total scattered power, defined as all light reflected in the polar scattering angle range of \(6^\circ\)–\(90^\circ\). Here, \(l_{\text{scattered}}\) represents the circular average of the intensities calculated in Equation 1 to account for measurements at other azimuth orientations, \(\theta_{\text{crit}}\) is the critical angle corresponding to the refractive index value of the encapsulant and \(\lambda\) is the wavelength of the incident light.

\[
f_T = \frac{\int_{\theta_{\text{crit}}}^{\theta_{\text{esc}}} \int_{\lambda=480}^{950} l_{\text{scattered}}(\theta_{\text{crit}}, \lambda) d\lambda d\theta_{\text{crit}}}{\int_{\theta_{\text{esc}}}^{\theta_{\text{crit}}} \int_{\lambda=480}^{950} l_{\text{scattered}}(\theta_{\text{crit}}, \lambda) d\lambda d\theta_{\text{crit}}}.
\]  

(Figure 10) shows the evolution of \(f_T\) for the fabricated random pyramidal texture (blue trace) with increasing encapsulant refractive index from 1 to 4, corresponding to a critical angle range from \(90^\circ\)–\(14.5^\circ\), along with \(f_T\) calculated for “theoretical” random pyramids (black trace) described in Table 1 with \(\alpha = 54.74^\circ\) (where reflectance weightings for each path were taken from other studies\textsuperscript{5,25}). Also plotted is \(f_T\) calculated from the pyramidal texture and the paths described in Table 2 (orange trace), where a range of dihedral base angles from \(51^\circ\)–\(53.2^\circ\) was considered, with reflectance weightings approximated from the power redistribution triggered by the disappearance of Paths B, E, and G (see Section 4.3 and Table 2). The pyramidal random texture with \(\alpha = 54.74^\circ\) (black trace) presents steps at fixed known scattering angles corresponding to various photon paths. In contrast, the fraction trapped for the experimentally measured pyramidal texture (blue trace) yields lower values for high refractive indices, and it is a much more continuous function. This is due to the wider scattering angle distribution, as well as the peak shift to lower scattering angles than those calculated. Moreover, the orange trace calculated according to the texture described in Table 2 is a much better approximation of the actual experimental data than the step function and shows the contribution of the different paths. However, for low encapsulant refractive index values (below 1.6, so critical angles above \(40^\circ\)), the presence of signals corresponding to high photon paths in the measured data causes the fraction trapped to be greater than that calculated considering only paths identified in Table 2. This is particularly important for PV applications where the typical encapsulant refractive index ranges from 1.45 to 1.55\textsuperscript{9}.

For a typical PV encapsulant of 1.5 refractive index, such as ethylene-vinyl acetate,\textsuperscript{27} the predicted fraction of light trapped using the measured scattering profile is 14.5% (blue trace), an increase over the 3.8% predicted from simulation of a pyramidal texture with a 54.74\textsuperscript{°} base angle. While pyramids with \(\alpha = 54.7\textdegree\) would achieve an \(f_T\) that exceeds 70% when the refractive index of the surrounding encapsulant is changed to 1.6, the smaller \(\alpha\) in fabricated random pyramid samples causes \(f_T\) to be much lower in practice. However, the high angle scattering found in experimental samples, that is not predicted by ray-tracing on ideal pyramids, enhances \(f_T\) for encapsulant refractive indices below 1.6. The implications of this at the device level are beneficial, as low absorption coefficients and low refractive index encapsulants are desirable for a silicon solar cell, in

![Figure 10](image-url)
order to prevent high reflectance and absorption from these layers. The data presented here may relax requirements when designing new interfaces and materials on top of the textured bulk. Alternatively, developments of etching processes that result in larger base angle pyramids are encouraged for an increase in the fraction of scattered light trapped in an encapsulated stack, while maintaining the industrial materials commonly used.

In general, for optical simulations of random pyramidal textures, a dihedral base angle distribution in the range of $49^\circ – 53^\circ$ with a peak at $52^\circ$ results in a better match to the angular dependent experimental data reported here and in previous work,$^{10}$ compared with a fixed base angle of $54.74^\circ$.

6 | CONCLUSIONS

WARS reflectance measurements for alkaline-etched silicon upright random pyramids are presented in this work. The measurements prove to be in good agreement with previous studies for fixed wavelengths, which show a maximum in the measured intensity for a scattering angle of approximately $28^\circ$, validating the data collected by our setup. FIB characterization reveals experimental dihedral base angles ($\alpha$) lower than the $54.74^\circ$ expected for the intersection between [111] and [100] planes, with an angle of $52.1^\circ \pm 1.1^\circ$ measured. A new scattering profile description is presented, showing that several of the photon paths disappear with such a decrease in the pyramid base angle. The implications of these findings at the silicon solar cell device level are discussed, mainly in terms of the fraction of scattered light trapped at the glass-air interface when the texture is encapsulated. Our results show that the predicted fraction of light trapped using the measured scattering profile is lower than that predicted by ray-tracing for large encapsulant refractive indices, but matches better if the morphology proposed (i.e., a range of pyramid slopes with lower $\alpha$) is taken into account. While simulations predict that the fraction of light trapped is only $3.8\%$ for a typical encapsulant with 1.5 refractive index, our experimental results show that this value is $14.5\%$ due to reflections arising at scattering angles $>50^\circ$.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

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