How cell textures impact angular cell-to-module ratios and the annual yield of crystalline solar modules

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A R T I C L E   I N F O

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A B S T R A C T

Two emerging trends in multicrystalline silicon cell texturing are plasma texturing, and metal catalyzed chemical etching. Both processes roughen silicon surfaces in order to increase light absorption. These processes are attractive as they are applicable to diamond-wire sawn wafers. This work investigates the optical properties of these surfaces, and other conventionally textured surfaces like isotropic acidic and random pyramid textures, are investigated for cells in air and after encapsulation for a large range of angles of incidence. We find that the angular optical performance in air varies strongly with cell texture, but when embedded in a module structure these variations are significantly mitigated: the advantages of a high angular absorption of solar cells are not fully transferred to the module level. This is especially notable for plasma etched, black silicon cell structures which suffer comparatively from poorer index matching and light recycling inside a module structure. The losses caused explicitly by the module embedding (described in the cell to module ratio) are in the range of 1–5% for perpendicular incoming light, and increase to 6–15% at an angle of incidence of 70°. Based on these angular performances, we calculate the annual yield of the modules and find that it varies by less than 2% for the cell textures. Nevertheless, the annual optical yield for the black silicon cell structures are the highest, whereas the metal catalyzed chemical etching cell structures show the lowest performance. Further, we find that different annual distributions of the incoming light at the two investigated locations (Melbourne and Alice Springs) only impact the relative performance of the cell textures at high module tilt angles.

1. Introduction

Key metrics of photovoltaic (PV) cell and module performance are efficiency and power, measured under standard test conditions (STC) with normal irradiance [1]. However, in-field performance strongly impacts the final levelized cost of PV electricity where most radiation is typically non-normal [2]. Clearly, different front solar cell textures impact angular light absorption [3,4]. However, it is the angular behavior of a cell embedded in a module laminate, and how the module embedding impacts the cell angular behavior that impacts field performance. Hence, to truly reduce costs by manipulation and design of the cell front surface, the performance after module embedding should be considered. This work investigates cell types with various front textures including chemical and plasma etched front structures, and compare them to common isotropic acidic and random pyramid textured wafers. We focus our work on recently developed black silicon cell structures, particularly metal catalyzed chemical etched (MCCE) textures applied on wire sawn multicrystalline wafers, and plasma etching on previously acidic textured wafers. Both technologies are currently under investigation in industry [5], especially the MCCE process which could lead to cost reductions and can be applied directly on diamond saw wafers [6–8].

Previous work [9–11] investigated the impact of acidic and random cell textures on module power under standard test conditions (STC) using an angle of incidence (AoI) of 0°. Other work [12,13] considered angular resolved cell and module measurements determined up to an angle of incidence of 60° and under the standardized sun spectra AM 1.5 g. In our study we show the angular resolved absorption of seven industrially relevant solar cell structures in air for angles of incidence up to 80°, which allows higher accuracy in determining the angular power output. Based on our measurements we compute the impact of embedding on the annual optical yield (AOY) of a module. Further, in [14] the performance of random, acidic, and honeycomb textured cells were investigated both in air and within a module structure, focusing...
on validating simulations by using external quantum efficiency (EQE) and reflectance measurements to determine the angular spectral power generation. In contrast, we use an experimental approach to investigate a wider range of industrial manufactured solar cells, focusing on black silicon structures. Particularly we examine the impact of the module design on angular absorption and derive from this the impact on the annual yield. We use two different common glass covers with and without an antireflective coating to demonstrate the impact on annual module performance for the seven different cell types under realistic angular distributions of light. To achieve this, we determine the optical losses caused by the module embedding (glass and Ethylene-vinyl acetate (EVA)) for various angles of incidence (AoI) quantified by the cell to module ratio (CTM), which is a parameter indicating optical losses explicitly caused by embedding and is described in [10,13,15].

2. Experimental approach

2.1. Samples

We investigate seven industrially processed solar cell structures from five different manufacturers (see Table 1). The cells are categorized according to their front texture, their rear structure, and the presence or absence of front side metallization. The back-end processing of the MCCE, black silicon, and isotextured samples is performed on the same pilot line using the same front and rear screen print parameters. This experimental design allows a direct comparison of these three cell types. In particular, it enables the determination of the impact of finger scattering on the module output or the CTM ratios.

We laser-cut the solar cells into samples of size $20 \times 17.5 \text{ mm}^2$. Later, we embed these into a standard module structure commonly used.
in large scale production using an EVA film designed for PV applications and a 2.9 mm thick low iron glass without antirefection coating. Following initial characterization, we apply a 0.5 mm thick MgF2 coating as an antireflection layer on the glass surface of the same samples.

To consider multiple light bouncing effects within the module, for example from light reflected at the finger surface, it is necessary to apply mirrors on the edge of the small module samples. The specular mirrors reflect the light back into the sample at the same angle. We use a mirror film optimized for solar applications supplied by company Alanod GmbH [16]. The mirrors are fixed with an acrylic transparent glue. Possible sources of measurement uncertainties caused by this approach are further discussed in Section 2.4.(Fig. 1)

2.2. Measurements

The global hemispherical reflectance of cells in air and inside a module structure is measured inside an integrating sphere using a centre mount sample holder (see Fig. 2). The light spot has a size of around 10 × 2 mm² at 8° and of around 10 × 10 mm² at 70° angle of incidence. The reflectance of all samples is determined at an angle of incidence of 8°, 20°, 40°, 60° and 70° degrees over a wavelength range from 250 nm to 1500 nm in 10 nm steps. For the samples in air, we additionally measure the reflectance at an AoI of 75° and 80°, which is not possible for the embedded samples due to restrictions in mounting the samples inside the sphere.

Since the bifacial and IBC cells partly transmit the light, we measure the reflectance in air with a black backsheet behind the cell. This backsheet is later part of the module structure and allows therefore a direct comparison of the measured values to determine the CTM ratio. All other samples have standard industrial aluminum pastes on the backside, with an opaque full-area screen-printed aluminum film.

Metallized samples are measured with the fingers orientated parallel to the axis of rotation such that the fingers do not lead to exacerbated cell shading at higher angles of incidence (see Fig. 2 right). We assume rotationally symmetric behavior of the cell textures.

2.3. Calculation of CTM ratio based on measurement

The cell to module ratio (CTM ratio) describes the gains or losses in power caused by embedding a cell in a module configuration. That is, the ratio between the light absorbed by a cell embedded in a module relative to the same cell surrounded by air. With the spectrophotometer we measure the reflectance of samples in air and embedded \( R_{\text{air}}(\lambda, \Theta) \) and \( R_{\text{module}}(\lambda, \Theta) \). However, we must determine the effective cell absorption by correcting the measured reflectance of a module sample with the light absorbed in the glass and EVA \( \alpha_{\text{glass}}(\lambda, \Theta) \) and \( \alpha_{\text{EVA}}(\lambda, \Theta) \). For this we employ the following approach:

\[
\alpha_{\text{cell,air}}(\lambda, \Theta) = 1 - R_{\text{air}}(\lambda, \Theta) \tag{1}
\]

\[
\alpha_{\text{cell,embedded}}(\lambda, \Theta) = (1 - R_{\text{module}}(\lambda, \Theta)) - \alpha_{\text{glass}}(\lambda, \Theta) - \alpha_{\text{EVA}}(\lambda, \Theta) \tag{2}
\]

where

\[
\alpha_{\text{glass}}(\lambda, \Theta) = (1 - R_{\text{air}}(\lambda, \Theta)) \cdot \alpha_{\text{glass}}(\lambda, \Theta) \tag{3}
\]

\[
\alpha_{\text{EVA}}(\lambda, \Theta) = (1 - R_{\text{air}}(\lambda, \Theta)) \cdot (1 - \alpha_{\text{glass}}(\lambda, \Theta)) \cdot \alpha_{\text{EVA}}(\lambda, \Theta) \tag{4}
\]

We follow the procedure described in [10] to determine the absorption of the EVA and glass. The CTM ratio is here defined as

\[
\text{CTM ratio} = \frac{\alpha_{\text{cell,embedded}}(\lambda, \Theta)}{\alpha_{\text{cell,air}}(\lambda, \Theta)} \tag{5}
\]

It is important to consider that the measured cell absorption in air and inside a module includes a proportion of light absorbed by the cell backside. This can be from the backside metallization (fired aluminum paste) or to a smaller degree by backside coatings (typically SiNx) [18]. Therefore, it is not valid to calculate the power output of a cell directly from the absolute cell absorbance. Nevertheless, it is possible to detect the change in power from the change in absorption before and after embedding. Assuming the fraction of light absorbed at the backside is the same we can calculate the change in absorption, and therefore the change in short circuit current and power.

2.4. Sources of measurement uncertainty

Since the cell to module ratio usually describes optical losses/gains in the range of ± 5% at perpendicular irradiances, it is necessary to understand and determine the possible sources of uncertainty, and to quantify them. Table 2 lists possible sources of measurement uncertainties, and describes the procedure to evaluate them.

For the reflectance in air and module \( (\lambda R_{\text{air}}(\Theta), \lambda R_{\text{module}}(\Theta)) \) at 8° and 70° AoI, we add each uncertainty factor \( U_n \) as follows:

![Fig. 1. Illustration of the module setup including dimensions.](image)

![Fig. 2. Illustration of the location of the sample holder inside the integrating sphere (left) and of the clamp sample holder itself (centre); right: photographic image of cell sample in air inside the integrating sphere [17] clamped into a centre mount sample holder.](image)
Table 2

<table>
<thead>
<tr>
<th>Type of uncertainty n</th>
<th>Description of measurement uncertainty $\Delta n$ and estimation of their impact on measurement results of $R_{air}$ and $R_{module}$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Measurement</td>
<td>Uncertainty of spectrophotometer work we assumed the most conservative value.</td>
</tr>
<tr>
<td>2. Repeatability</td>
<td>Baseline measurement and 10 repeated measurements negligible.</td>
</tr>
<tr>
<td>3. Inhomogeneity</td>
<td>Light spot area increases with higher AoIs. Cell surface is inhomogeneous, and the actual sample spot measured in air differs from the spot measured inside the module. We measure two different areas of the module at 8° and 70°.</td>
</tr>
<tr>
<td>Impact of mirrors</td>
<td>We used a solar mirror with a weighted reflectance of 96.5% and we bond to the glass edge with acrylic glue with a transmittance of 97.8%. During the sample manufacturing, we must assume the glue might include air voids and the mirror is not perfectly parallel to the glass edge, which might lead to partly diffuse reflection and partly direct reflection at a slightly incorrect angle. For determining this effect, we measure cell sample D once by backside reflectance measurements at different angles of incidence based on measurements at 8° and 70° AoI.</td>
</tr>
<tr>
<td>Impact of di↵erent</td>
<td>We determine these errors through measurements at 8° and 70° AoI and inter-/extrapolated linearly for the other angles (see Table 3). Further, we give an estimation of their impact on the final absorption values and CTM ratios by using linear error propagation [20] (see Fig. 4 and 5):</td>
</tr>
<tr>
<td>Impact of EVA EVA</td>
<td>By assuming that the uncertainty of absorption values of glass and EVA ($a_{EVA}(\lambda, \theta), a_{glass}(\lambda, \theta)$) (see Eqs. 3 and 4) is insignificant to others, the following applies:</td>
</tr>
<tr>
<td>Impact of cell</td>
<td>The impact of this effect is determined by shifting the sample up and down. For structures D and G, part of the light is transmitted through the backsheet, and the black backsheet is not an ideal absorber. It reflects 4.8% of the light measured in air at an AoI of 0°. Being embedded in the module structure, absorption of EVA and glass at different angles of incidence might vary slightly from module to module.</td>
</tr>
<tr>
<td>Impact of fingers</td>
<td>The other angles are linearly inter-/extrapolated. These values are used as error bars in Fig. 4(a) to (c). The values are given separately for samples D and G since these are semi-transparent.</td>
</tr>
</tbody>
</table>

Table 3

Determined uncertainties for the absorption of a cell in air and inside a module over the relevant angles of incidence based on measurements at 8° and 70° AoI. The other angles are linearly inter-/extrapolated. These values are used as error bars in Fig. 4(a) to (c). The values are given separately for samples D and G since these are semi-transparent.

<table>
<thead>
<tr>
<th>$\theta$ (°)</th>
<th>$\Delta a_{cell,air}(\theta)$ (%)</th>
<th>$\Delta a_{cell,embedded}(\theta)$ (%)</th>
<th>$\Delta a_{cell,air}(\theta)$ (%) samples D &amp; G</th>
<th>$\Delta a_{cell,embedded}(\theta)$ (%) samples D &amp; G</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>± 1.05</td>
<td>± 1.33</td>
<td>± 1.07</td>
<td>± 1.35</td>
</tr>
<tr>
<td>20</td>
<td>± 1.22</td>
<td>± 1.66</td>
<td>± 1.24</td>
<td>± 1.68</td>
</tr>
<tr>
<td>40</td>
<td>± 1.39</td>
<td>± 1.99</td>
<td>± 1.41</td>
<td>± 2.01</td>
</tr>
<tr>
<td>60</td>
<td>± 1.55</td>
<td>± 2.33</td>
<td>± 1.57</td>
<td>± 2.35</td>
</tr>
<tr>
<td>70</td>
<td>± 1.57</td>
<td>± 2.36</td>
<td>± 1.59</td>
<td>± 2.38</td>
</tr>
<tr>
<td>80</td>
<td>± 1.72</td>
<td>± 1.74</td>
<td>± 1.70</td>
<td></td>
</tr>
</tbody>
</table>

$$\Delta R_{air} = \Delta U_{1} + \Delta U_{1}(air)$$

$$\Delta R_{module} = \Delta U_{1} + \Delta U_{1}(module)$$

By assuming that the uncertainty of absorption values of glass and EVA ($a_{EVA}(\lambda, \theta), a_{glass}(\lambda, \theta)$) (see Eqs. 3 and 4) is insignificant to others, the following applies:

$$\Delta a_{cell,air}(\theta) = \Delta R_{air}(\theta)$$

$$\Delta a_{cell,embedded}(\theta) = \Delta R_{module}(\theta)$$

We determine these errors through measurements at 8° and 70° AoI and inter-/extrapolated linearly for the other angles (see Table 3). Further, we give an estimation of their impact on the final absorption values and CTM ratios by using linear error propagation [20] (see Fig. 4 and 5):

$$\Delta CTM(\theta) = \left| \frac{\delta CTM}{\delta a_{cell,air}(\theta)} \Delta a_{cell,air}(\theta) + \frac{\delta CTM}{\delta a_{cell,embedded}(\theta)} \Delta a_{cell,embedded}(\theta) \right|$$

Nomenclature for Section 2.3 and 2.4

- $R_{air}(\lambda, \theta)$: measured spectral reflectance of samples in air
- $R_{module}(\lambda, \theta)$: measured spectral reflectance of samples embedded in a module
- $R_{air, glass}(\lambda, \theta)$: first reflection the interface air/glass
- $a_{EVA}(\lambda, \theta)$: absorption of EVA surrounded by air
- $a_{glass}(\lambda, \theta)$: absorption of glass surrounded by air
- $a_{EVA, glass}(\lambda, \theta)$: effective absorption of glass
- $\alpha_{cell}(\lambda, \theta)$: effective absorption of EVA
- $\alpha_{cell,air}(\lambda, \theta)$: absorption of cell surrounded by air
- $\alpha_{cell,embedded}(\lambda, \theta)$: absorption of cell embedded in a module structure
- $\lambda$: wavelength
- $\Theta$: angle of incidence (AoI)
- $U_n$: uncertainty of effect n

3. Experimental results

3.1. Angular reflectance and absorbance of cells in air and module

3.1.1. Global hemispherical reflectance

Fig. 3 plots the spectral reflectance measurements at different angles for three samples: the MCCE on diamond sawn wafer; isotextured wafers with an additional plasma texturing (black silicon); and standard isotextured multicrystalline cells. The cell types are identical in their
rear metallization printing and their front finger printing, enabling a direct comparison.

For an AoI of 8°, the lowest reflectance is detected for the black silicon cells peaking at 2.7% at 560 nm compared to 3.2% at 670 nm for the MCCE, and 2.9% at 580 nm for the standard acidic texture. Further, the slope in reflectance between 400 and 1000 nm is stronger for the MCCE and isotexture compared to the black silicon cell. For increasing AoI the reflectance curves shift upwards, and while the black silicon only shows an increase in its minimum reflectance up to 5.2% (equals 2.5% difference from 8° to 70°), the MCCE texture increases up to 12.7% (equals 9.5% difference) and the isotexture up to 7.0% (equals 4.1% difference).

At the relevant wavelength range from 400 to maximum 1200 nm, spectral variance in the module embedding is significantly decreased, especially for module configurations without an antireflective glass coating. Below 400 nm, the absorbance of the glass and EVA reduces the measured reflectance in all cases. The antireflective glass coating impacts the spectral reflectance in such a way that it shifts the minima to significantly higher wavelength ranges (e.g. the MCCE texture moves its local minimum from 5.5% at 690 nm without AR coating to 3.7% at 900 nm with AR coating).

Note that the reflectance curves of all samples can be found in Appendix A. Also note that the deflection of the measured reflectance curves in the wavelength range of 850–880 nm, especially at high AoIs, is caused by a detector change in this range. For calculating the effective absorption curves (see Section 3.1b), we correct the curves by using a linear interpolation between 850 and 880 nm.

3.1.2. Effective (weighted) angular absorbance

By weighting the measured absorption curves with the AM 1.5g spectrum (in Wm⁻² nm⁻¹) and the cells internal spectral response (in A/W), we determine the effective angular absorption (see Fig. 4). The internal spectral response is taken from the internal quantum efficiency (IQE) of a high efficiency IBC solar cell. A cosine correction is not necessary since the area of the incoming light spot is smaller than the measured cell area for all angles of incidence, so the light spot falls entirely into the sample area. For the samples measured in air, the black silicon sample shows the highest absorption over all AoIs, decreasing from 94.6% at 8° down to 82.3% at 80°. Isotextured and MCCE on diamond cut wafers show the lowest absorption, decreasing from 90.8% / 91.3–61.2% / 75.9% (see Fig. 4a). Looking to the normalized absorption curves in air (see Fig. 4d), the black silicon cells and the random PERC samples show the smallest decrease in absorption, both retaining 87% of their initial performance at 8° AoI. The worst angular performance is found for the two MCCE textured diamond cut wafers. Their normalized absorption decreases down to 67% and 70% respectively at 80°.

By putting the cell samples into a typical module setup, the spreading of the angular absorption between the cell types is significantly reduced for all angles of incidence. For example, the MCCE vs. black silicon cell samples vary in their absorbance in air at 70° by an absolute of 10.4% which reduces to 2.2% after module embedding without AR coating and 2.5% with AR coating (see Fig. 4b and c). Looking to the normalized absorption curves (d–f), it becomes even more obvious that embedding reduces the variance between different
cell textures to a minimum, even for high angles of incidence. This means that the advantage of a high angular absorption in air (for example of the black silicon texture) is nearly not transferred to the module level. This is the general case for all high-performing cell textures, which suffer more from embedding compared to the initially worst performing MCCE structures.

This behavior is explained by the photon recycling effects during embedding, which help cells with an initial high reflectance loss to couple relatively more light into the cell after embedding, whereas cells with an initially low reflectance loss in air do not experience such a large coupling gain. This effect is further described in [10].

Further, the change in angular absorption can be explained by considering that the ability to absorb angular light inside a module is mainly driven by the reflectance on the glass/air interface. For example, in a module setup without AR coating the cells can absorb up to 73–75% at an AoI of 70° (see Fig. 4b). Given that at this AoI the air/glass reflectance losses are known to reduce the absorbance by about 18%, the other 7–9% must be caused by reflection and absorption losses within the module structure. Due to the higher refractive index of glass ($n_{\text{glass}} = 1.52$) and EVA ($n_{\text{eva}} = 1.47$), light incident at shallow angles to the module surface is refracted in the direction of steeper angles to the surface (Fresnel law [21]). For example, an AoI of 70° will lead to an incoming angle at the cell surface of only 38°. At this AoI the cells still absorb more than 97% relative to perpendicular irradiance (see Fig. 4d). Note that applying an anti-reflective coating on the glass surface changes the amount of light entering a module, but does not affect the angle at which the light hits the cell surface, since this is determined by the refractive index of the embedding material which directly surrounds the cell.

### 3.2. Angular cell to module (CTM) ratio

Focusing more closely on the optical losses caused by particularly the module embedding, we use the CTM ratio which relates the cell absorption within a module to the absorption measured in air at the same AoI (see Fig. 5).

For modules without an antireflective coating, we determine CTM ratios between 0.95 for the black silicon texture and up to 0.98 for isotexture at an AOI of 8°. That is, the reflection losses at the air/glass surface and the absorption in glass and EVA cause 5% reduction in power in the case of black silicon solar cells, but only 2% for the isotextured solar cells having the same front metallization.

According to the CTM ratios over increasing AoIs, it is obvious that the black silicon cells have the lowest CTM ratios across all angles. The CTM ratio for this cell type at 70° AoI is 0.85, while it is still 0.93 for the MCCE texture. The latter can be explained by their high initial absorption losses at high AoIs in the air, which do not decrease further when embedded.

Applying an AR coating to the glass increases the CTM ratios by an average of 0.02 for 8°, 20° and 40°, and 0.04 at 70° AoI. This allows CTM ratios above 1 to be achieved, which means that embedding the module produces a gain over samples measured in air. This applies in particular to isotextured and bifacial samples (see Appendix C).

By comparing MCCE and isotextured samples with and without finger metallization (Fig. 6) we determine the influence of front metallization on the CTM ratio for different angles. We see that the CTM...
ratios are higher across all AoIs for samples with front metallization. For MCCE wafers, the CTM ratio increases by 1% and for the isotextured samples by 1.8% at an AoI of 8°. This is expected, as the light incident on the fingerprint is usually lost during measurement in air, but can return back onto the cell surface after embedding. Furthermore, we find that the change in the CTM ratio caused by the fingerprint is higher at an AoI of 70°.

4. Calculation of the annual optical yield

4.1. Approach

Using the software SunCalculator [22], we calculate the angular resolved irradiance received on a tilted module plane as a function of the module tilt. Based on annual irradiances, we calculate the theoretical annual optical yield (AOY) of a cell exposed directly in air, and inside a module. We chose two Australian locations: one with a higher diffuse to global irradiance ratio of 40%, Melbourne, and one with a significantly lower ratio of 21%, Alice Springs (see Fig. 7). We use solar irradiance data provided by the Australian Bureau of Meteorology (BoM) [23]. Further, we look at a module installed at its optimum tilt (32.5°N for Melbourne and 22.5°N for Alice Springs), and a 90° tilt angle representing a façade installation.

We calculate the AOY of a cell in air / module by summing the angular resolved spectral irradiance multiplied with the absorption spectra over the AoI [24]. For the absorption in air, we measure up to an AoI of 80° and then use a linear interpolation fit. The absorption at an AoI of 90° was set to 0. For the absorption in a module we fit the measured curves using the Martin Ruiz model [25].

We define the annual optical yield (AOY) as the energy yield, which only considers optical losses and neglects electrical losses (such as fill factor losses or module mismatch). We assume that the power output of a module is directly proportional to the amount of light absorbed by the solar cell weighted with the IQE. This implies that the influence of irradiance on the fill factor and open-circuit voltage caused by the

Fig. 5. Optical losses caused by the module embedding (CTM ratios) for both module configurations for 5 of the investigated cell samples. The CTMs tend to decrease for higher angles, with some exceptions. The CTM ratios for the samples embedded with AR coated glass are on average 2% higher than the same samples embedded without AR coating. (see APPENDIX C for all samples).

Fig. 6. Impact of fingerprinting on CTM ratios for 8° and 70° AoI for a cell with MCCE on diamond sawn wafers and a standard isotextured ALBSF structure with identical finger prints.

Fig. 7. Cumulative direct and diffuse annual irradiance at the optimum tilt angle and at 90° tilt (façade) plotted for Melbourne and Alice Springs. Within Australia these places represent locations with one of the highest components of diffuse (Melbourne) or direct irradiance (Alice Springs).
Fig. 8. Annual optical yield (AOY) normalized to the theoretical yield of an ideal solar cell with a spectral absorption of 1. The yield is calculated for a location with high direct irradiance (Alice Springs) and high diffuse irradiance (Melbourne) for modules installed at optimum tilt and integrated into a façade with a 90° tilt. For all locations and tilts, the black silicon cell structures in air reach a significantly higher annual yield (5% more than MCCE multi cell). When embedded in a module, the cell types show an annual yield which then only spreads by less than 2% between the highest and the lowest.

Fig. 9. Annual yield losses attributed to angular effects inside the module shown for two locations and for two different tilt angles. A standard module embedding without ARC reduces the annual yield by 5–8% and up to 13% being installed inside a façade due to insufficient angular light capturing.
changes in irradiance due to embedding is small (< 10%). We note that even if these parameters change minimally with irradiance, their impact will be minor in a relative comparison provided these changes are similar for the different cell types. Publications describing the effect of illumination on the fill factor can be found in [26,27].

As a reference, we further calculate the annual optical yield for an ideal cell with an assumed spectral absorption of 1, representing a cell with no optical or internal electrical losses (IQE = 1 and absorption = 1). In Fig. 8, we plot the AOY of each configuration in reference to this maximum “ideal” AOY (y-axis = 1 in Fig. 8) which enables a direct comparison of all the cell structures and embedding options.

4.2. Results

Fig. 8 shows black silicon cell structures surrounded by air achieve the highest annual yield for all locations and tilt angles. Compared to the worst performing MCCE cell structure, the yield advantage of a black silicon cell is in the range of 5%. After embedding the cells in a module, the yield decreases in the range of 4–7% for all cell types, and 2–5% for ARC-coated modules. Nevertheless, the black silicon structures always achieve the highest annual yield for all slopes and locations, even if their yield advantage after embedding in a module is reduced to less than 2% compared to the other cell types.

Comparing the two investigated module tilts (cf. upper and lower graph in Fig. 8), the annual yield is reduced by up to 6% if the module is installed inside a façade. Due to the higher angles of incidence (see Fig. 7), the yield losses caused by the module embedding reach values of up to 10% for a black silicon cell.

Although the angle distribution of irradiance is very different for both sites, the AOY is similar for all cell types (< 0.3% difference between Alice Springs (right side Fig. 8) and Melbourne (left side Fig. 8)). For example, a random pyramid textured PERC cell in air would achieve 90.7% yield of an ideal cell structure in Melbourne compared to 90.8% if the same cell was installed in Alice Springs.

By comparing the AOY values (Fig. 8 top graphs) with the angle absorption curves (Fig. 4b and c), we derive the angle at which a module is to be measured in order to predict the annual power as accurately as possible for a module installed at optimum tilt. We find these angles to vary between 45° and 53° for uncoated modules and between 55° and 58° for AR-coated modules.

We calculate the annual angular yield losses by subtracting the AOY of each configuration from the yield that any cell structure would achieve in air without angular losses. So here, we assume a constant angular absorption curve based on the value at 8° AoI (see Fig. 9).

The annual angular losses due to the module embedding are in the range of up to 8% at optimum inclination, and up to 14% for façade installations. We also find that the module-related yield losses of the isotextured and MCCE-textured cells are significantly lower than for the black silicon structure, due to the initially poorer angular light trapping behavior. Although the cells/modules in Melbourne are exposed to a wider distribution of incident light than in Alice Springs, the angular yield losses differ by only about 2% at an inclination of 90°, while the difference at optimum inclination never exceeds 0.2% (see left and right sides of Fig. 9).

5. Summary and conclusion

As a main result, we find that the wide spread of angular absorption seen in air is significantly reduced for all cell types after being embedded in a module (air: Δ = 3.8% at 8°, Δ = 10% at 70°; module: Δmax = 2.3% at 60°). Therefore, the optical advantages of the black silicon structures in air are minimized at module level. In fact, all cell textures show almost the same angular absorption after embedding. This means that it is not possible to transfer a high angular absorption of the cell textures fully into a module structure using the here investigated embedding materials. Those experimental results can be explained by two effects: First, the angular absorption of cells within a module is mainly determined by the reflection losses at the air/glass interface. Second, diffraction of light into a module results in a maximum angle of incidence at the cell/embedding interface of 42.8° according to Fresnel equations (at a refractive index of 1.47 for the embedding material). Since the absorption curves of the cells only vary greatly above this angle, the variation in air after embedding is insignificant.

Furthermore, we find that applying an AR coating to the module glass surface increases absorption by an average of 1.6% with an AoI of 8° and 3.6% with an AoI of 70°.

Focusing particularly on losses caused by module embedding, we find CTM ratios between 0.95 for plasma-etched cells and 0.98 for isotextured cells at perpendicular irradiance. The CTM ratio decreases slowly up to an AoI of 60°, then more drastically for higher Aois to 0.85 (black silicon cells) or at best 0.93 (MCCE cells). By applying an anti-reflective coating to the glass surface, CTM ratios of 1 can be achieved for ISO and MCCE textures, resulting in constant performance before and after embedding.

For the annual optical yield, we find that although the black silicon structure suffers most from embedding in a module (~7% for AOY), this cell type still achieves the highest annual yield regardless of whether it is installed at optimum inclination or within a façade.

As expected from the similar angular absorption curves, the annual yield of the cell structures shows similar performances once embedded. Compared to the best performing cell, the worst performing embedded cell achieves only 1.6% less yield.

The annual angular yield losses attributed to module embedding range from 3% to 8% for optimum module tilt, with the highest losses due to the embedding of plasma-etched black silicon cell structures. When a module is installed in a façade, these angular losses increase significantly up to values of 14%.

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Fig. A1. Measured spectral reflectance curves for the nine investigated cell and wafer samples for different angles of incident (AoI) in air and embedded in modules with and with antireflective (MgF$_2$ = 94 nm) front coating.
Appendix B

See Fig. B1

Fig. B1. Absolute (a-c) and normalized (d-f) weighted angular absorption curves exemplary plotted for all the investigated cell structures. The cells show a wide spreading when surrounded in air but when embedded into a module (with or without ARC) the variance in angular absorption is significantly reduced so that all cell structures perform nearly the same. Graph (e) and (f) show nearly no spreading of the cells.

Appendix C

See Fig. C1

Fig. C1. Optical losses caused by the module embedding (CTM ratios) for both module configurations for all the investigated cell samples. The CTMs tend to decrease for higher angles, with some exceptions. The CTM ratios for the samples embedded with AR coated glass are on average 2% higher than the same samples embedded without AR coating.
References


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