MODELING THE THERMAL ABSORPTION FACTOR OF PHOTOVOLTAIC/THERMAL COMBI-PANELS

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ABSTRACT

A photovoltaic/thermal combi-panel is a device which converts solar energy into both electricity and heat. In such a device solar cells are used to generate electricity. Absorbed solar energy, which is not converted into electricity, is available in the form of residual heat. This heat is extracted from the combi-panel and made available for tap water heating or space heating.

If in a photovoltaic/thermal combi-panel standard solar cells are used, which inherently are poor absorbers of long wavelength irradiance, this results in a relatively low thermal efficiency. In order to increase this thermal efficiency significantly, the absorption of long wavelength irradiance needs to be increased either at cell level or at panel level.

There are two strategies to increase the long wavelength absorption. The first strategy is to use a second absorber behind a semi-transparent solar cell. The second strategy is to absorb irradiance in the back contact of the solar cell.

In order to determine how much each of these two strategies increases the thermal absorption factor, a computer model was developed. The model is one-dimensional and it takes multiple reflections and diffuse reflection into account.

This computer model was used to simulate various crystalline silicon solar cell configurations. It was found that a standard untextured solar cell with a silver back contact has an absorption factor of only 74%. If a semi-transparent solar cell is used in combination with a second absorber, the total absorption factor can increase to 87%. And if irradiance is absorbed in the back contact, the absorption factor can increase to 85%. In order to do so, rough interfaces are applied in combination with a non-standard metal as back contact.

It is concluded that both strategies can increase the amount of long wavelength irradiance absorbed by a photovoltaic/thermal combi-panel significantly.

INTRODUCTION

A photovoltaic cell has a typical efficiency of 5 to 20%. This means that the remaining 80 to 95% of the energy is in principle available in the form of heat. In a photovoltaic/thermal (PVT) combi-panel one tries to collect this heat as good as possible (Helden et al, 2004). Various PVT combi-panel designs were investigated by Zondag et al (2003). The simplest design is similar to a solar thermal collector of which the black absorber is replaced by encapsulated solar cells. Heat is extracted from the panel by a heat-transporting medium like water or air.

A typical solar cell configuration consists of a glass cover, a top grid, an anti-reflection (AR) coating, a semiconductor and a back contact. Absorption in the semiconductor takes place only for photon energies above a certain threshold energy, called the bandgap energy. Long wavelength irradiance, with photon energies below this bandgap energy, is hardly absorbed at all. This implies that the absorption factor of the semiconductor is significantly lower than of a black absorber, which has an absorption factor of approximately 95%. Therefore a PVT combi-panel has a relatively low thermal efficiency. But this efficiency will increase significantly if the absorption of long wavelength irradiance is increased either at combi-panel or at cell level.

The first strategy that can be used to increase long wavelength absorption is to use semi-transparent solar cells followed by a second absorber. This is illustrated in the left panel of
figure 1. A solar cell can be made semi-transparent by omitting the back contact. In this way the short wavelength irradiance, indicated by the dotted arrow, is absorbed in the solar cell, represented in a simple way by semiconductor (s). However, the long wavelength irradiance, indicated by the solid arrow, is transmitted and can then be absorbed by the second absorber (a).

The second strategy is to increase the amount of long wavelength irradiance that is absorbed in the back contact of the solar cell. This is illustrated in the right panel of figure 1. This can be done by using rough semiconductor-interfaces, which reflect and transmit irradiation diffusely, thereby providing optical confinement of the long wavelength irradiance. This increases the chance for absorption in the metal back contact (m).

To determine whether these strategies are successful, a computer model was developed which can predict the absorption and transmission factor of different solar cell configurations. The model takes multiple reflections and diffuse reflection into account.

First the methodology of the model is described. Then results from the model are presented and discussed.

**Figure 1**: Cross-sections of solar cell configurations applying strategy 1 (left) and strategy 2 (right). g=glass, s=semiconductor, h=heat-transporting medium, a=second absorber, m=metal back contact.

**METHODOLOGY**

A solar cell configuration is represented by a one-dimensional multi-layer structure. This means that it can be defined by specifying the materials and the corresponding thicknesses for each layer. For example a standard solar cell configuration could be represented in the following way: glass (3000 µm), silicon nitride (0.06 µm), silicon (300 µm), silver back contact (5 µm). Here the silicon nitride film serves as an AR-coating and such thin films are treated differently from the other layers, as will be explained.

Consider a multi-layer structure of which the layers (l) and interfaces (i) are numbered as indicated in figure 2. Each layer l has a complex refractive index \( N_l \) given by,

\[
N_l = n_l - ik_l, \tag{1}
\]

where \( n_l \) is the real refractive index and \( k_l \) is the extinction coefficient. Note that \( N_l \) is a function of wavelength and can be found in literature for many materials (Palik, 1985).

First individual interfaces and layers are treated, and then it will be described how the absorption factor of such a multi-layer structure is determined.

**Interfaces**

Irradiance incident on an interface between two media is partly reflected and partly refracted. Both the direction and intensity of the refracted irradiance are functions of \( N_l \), as will now be explained.

For a given angle of incidence \( \theta_0 \) and incident medium characterized by \( N_0 \), the angle \( \theta_l \) can be calculated for each layer \( l \) using,

\[
\sin \theta_l \sin \theta_0 = \frac{N_0}{N_l} \tag{2}
\]

If \( N_l \) is real, then \( \theta_0 = \theta_l \), \( \theta_0 \) being the angle of refraction of layer \( l \). However, if \( N_l \) is complex, then \( \theta_l \) will be complex, and a procedure described by Born and Wolf (1999) is needed to derive the real refraction angle \( \theta_0 \) from the complex angle \( \theta_l \).

The reflectance \( r \) of an interface is defined as,

\[
r = \frac{I_{\text{ref}}}{I_{\text{inc}}}, \tag{3}
\]

where \( I_{\text{inc}} \) and \( I_{\text{ref}} \) are the intensity of the incident and reflected irradiance, respectively. The reflectance \( r_i \) corresponding to interface \( i \), for \( p- \) and \( s- \) polarized irradiance, is given by Fresnel’s intensity coefficient,

\[
r_i = \frac{\eta_{i+1} - \eta_{i}}{\eta_{i+1} + \eta_{i}}, \tag{4}
\]

Here \( \eta_i \) are the modified refractive indices given by

\[
\eta_i = \begin{cases} N_i/\cos \theta_i & \text{for } p\text{-polarization} \\ N_i \cos \theta_i & \text{for } s\text{-polarization} \end{cases} \tag{5}
\]
It will be assumed that solar irradiance is unpolarized, i.e. contains equal amounts of p- and s-polarized irradiance.

**Anti-reflection coatings.** Anti-reflection coatings consist of one or more coherent films on an interface to reduce its reflectance. Films are coherent when the optical thickness is smaller than the coherence length of the incident radiation, which is in the order of 1 \( \mu \text{m} \) for solar irradiance. When this is the case interference occurs between multiple reflections in the film. This influences the reflectance of the interface and this effect is exploited in AR-coatings.

Macleod (1986) has described a procedure for finding the reflectance of a coated interface. The modified refractive indices of the coherent films and the refracting medium \( n_l \) are combined in an effective refractive index \( N_l \). This index is used to find the reflectance \( r_i \) of the coated interface,

\[
r_i = \frac{n_{l+1} - N_l}{n_{l+1} + N_l}^2.
\]  

(6)

**Layers**

The transmittance \( \tau \) of a layer is defined as,

\[
\tau = \frac{I_l}{I_0},
\]

(7)

where \( I_0 \) is the intensity of an incident beam just below the top interface of the layer and \( I_l \) is the intensity of the beam when it reaches the bottom interface of the layer. The transmittance \( \tau \) of layer \( l \) can be calculated using the Lambert-Beer law,

\[
\tau_l = \exp(-\alpha d \cos \phi),
\]

(8)

Here \( d \) is the thickness of the layer and \( \alpha \) is the absorption coefficient given by,

\[
\alpha = 4\pi k / \lambda.
\]

(9)

**Multi-Layer Structure**

In order to determine the absorption factor of an entire multi-layer structure, including the effect of multiple reflections between the various interfaces, the net-radiation method is used. First it will be explained how this method works in the special case that all reflections are specular. Then it will be explained what changes when rough interfaces are involved, which reflect irradiance diffusely.

**Specular reflection.** First incident and outgoing fluxes are defined at the top and bottom of each interface. In figure 3, a simple example is shown. It should be emphasized that each flux represents the net radiation, i.e. each flux represents the sum of contributions from multiple reflections.

Flux \( q_{1a} \) incident from the top is set to unity and flux \( q_{2c} \) incident from the bottom is set to zero. All fluxes are related through a set of linear equations in which \( \tau \) and \( r \) occur which were determined earlier,

\[
\begin{cases}
q_{1a} = 1 \\
q_{1b} = r_t q_{1a} + t_1 q_{1c} \\
q_{1c} = \tau_1 q_{1b} \\
q_{1d} = r_t q_{1c} + t_1 q_{1a} \\
q_{2a} = \tau_1 q_{1d} \\
q_{2b} = r_2 q_{2a} + t_2 q_{2c} \\
q_{2c} = 0 \\
q_{2d} = r_2 q_{2c} + t_2 q_{2a}
\end{cases}
\]

(10)

where \( t = 1 - r \). This set of linear equations is solved simultaneously to find all fluxes. This is done by applying a Gauss elimination procedure for the equations written in matrix form.

**Figure 3:** Numbering of the fluxes for a simple configuration with two smooth interfaces.

Next the spectral reflection factor \( R_\lambda \), the spectral absorption factor \( A_\lambda \), and the spectral transmission factor \( T_\lambda \) are determined,

\[
\begin{align*}
R_\lambda &= q_{1b} / q_{1a} \\
A_\lambda &= (q_{1d} - q_{2a} + q_{2b} - q_{1c}) / q_{1a} \\
T_\lambda &= q_{2d} / q_{1a}
\end{align*}
\]

(11)

Since \( N \) is a function of \( \lambda, \tau \) and \( r \) will also be functions of \( \lambda \). As a result the spectral reflection, absorption and transmission factors \( R_\lambda, A_\lambda, \) and \( T_\lambda \) will also be functions of \( \lambda \). This is indicated by the \( \lambda \)-subscripts. In the model these values are determined for approximately 120 wavelengths between 0.1 and 5 \( \mu \text{m} \). For each wavelength the set of equations is solved to determine \( R_\lambda A_\lambda \) and \( T_\lambda \).
Finally the spectrum weighted reflection absorption and transmission factors \( R, A_t \) and \( T \), are found by integrating over the solar spectrum \( I_\lambda \):

\[
R = \int R_\lambda I_\lambda d\lambda / \int I_\lambda d\lambda
\]
\[
A_t = \int A_{t,\lambda} I_\lambda d\lambda / \int I_\lambda d\lambda
\]
\[
T = \int T_\lambda I_\lambda d\lambda / \int I_\lambda d\lambda .
\] (12)

In the model the standard AM 1.5 solar spectrum is used as defined by Hulstrom (1985).

**Diffuse reflection.** Semiconductor interfaces are often rough in order to increase the absorption factor of solar cells. These interfaces reflect and transmit irradiance diffusely. The irradiance that is reflected outside the critical angle cannot escape and is trapped. The critical angle \( \varphi_{cr} \) is defined by,

\[
\sin \varphi_{cr} = n_g / n_l .
\] (13)

It is assumed that for a given angle of incidence, a rough interface reflects the same amount of irradiance as a smooth interface. However the reflected intensity is reflected over all directions of a hemisphere. The angular intensity distribution \( I(\varphi, \theta) \) is estimated using the Phong model (Phong, 1975),

\[
I(\varphi, \theta) \propto r \cos^m (\gamma) .
\] (14)

Here \( r \) is the reflectance of a smooth interface and \( \gamma \) is the angular distance between the specular direction and an angular position on the hemisphere defined by \( \theta \) and \( \varphi \). Each interface in the multi-layer structure is given a roughness coefficient \( m \). Note that a higher \( m \) corresponds to a smoother interface which reflects irradiance in a more specular way, i.e. \( I(\varphi, \theta) \) forms a narrower spike in the specular direction. Burgers (1997) showed that a model using the Phong approach can successfully be used to fit experimental reflectance data.

Since irradiance no longer travels exclusively in the direction \( \varphi_0 \), in the model this angle is replaced by a set of angles. If for example this set is \( (\varphi_1, \varphi_2, \varphi_3) \), then each flux is replaced by a set of sub-fluxes \( (q_{1a}, q_{2a}, q_{3a}) \), as illustrated in figure 4.

For a given incident sub-flux each exiting sub-flux can be found by integrating \( I(\varphi, \theta) \) over the corresponding part of the hemisphere. Details will not be given here. What is important is that just as in the specular case, all sub-fluxes are related by a set of linear equations, which can be solved in a similar way to find the sub-fluxes.

Once the sub-fluxes are found it is convenient to sum them over all angles,

\[
\sum_{\varphi, \theta} q_{ia} = q_{ia,z} ,
\] (15)

so for each interface there are again four fluxes as in the specular case, shown in figure 3. Then eq. (11) and (12) are used to find \( R, A_t \) and \( T \). In the example of figure 4, each flux consists of only three sub-fluxes. However, in the model each flux is divided into 15 to 30 sub-fluxes. This means the angular resolution is between \( 3^\circ \) and \( 6^\circ \), which was found to be enough for the desired accuracy of 1%.

**RESULTS**

The model is used to find the absorption and transmission factors of various crystalline silicon solar cell configurations, given in table 1. First a standard solar cell with smooth interfaces and a silver back contact is simulated. This is configuration 1. The results are shown in figure 5. As expected, for long wavelength irradiance (\( \lambda > 1.1 \mu m \)) the spectral absorption factor of the silicon wafer \( A_{Si,\lambda} \) is almost zero. The low spectral absorption factor for the silver back contact \( A_{Ag,\lambda} \) indicates that almost no irradiance is absorbed by the silver.

**Table 1:** The crystalline silicon solar cell configurations that were simulated and their overall absorption factors \( A_{tot} \).

<table>
<thead>
<tr>
<th>Nr.</th>
<th>glass (3000 µm)</th>
<th>ARC (0.06 µm)</th>
<th>Si (300 µm)</th>
<th>roughness coef.</th>
<th>ARC (0.17 µm)</th>
<th>back cont. (5 µm)</th>
<th>( A_{tot} ) (%)</th>
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<tr>
<td>1</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
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<td>✔</td>
<td>✔</td>
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<td>✔</td>
<td>✔</td>
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<td>Pt</td>
<td>85</td>
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Figure 5: The spectral absorption ($A_\lambda$) and reflection ($R_\lambda$) factors for configuration 1.

As a result the spectral reflection factor ($R_\lambda$) is high for the long wavelength irradiance and hence the overall absorption factor for configuration 1 is only 74%.

The model will now be used to find the absorption factor for alternative crystalline silicon solar cell configurations. As explained in the introduction, there are two strategies that can be followed: use of a second absorber or use of improved absorption in the back contact.

Strategy 1: Use of a Second Absorber

In order to make solar cells semi-transparent the back metallization is replaced by a metallic grid, similar to the top-grid. The influence of this back-grid on the absorption of irradiance is small and it is ignored here just like the influence of the top-grid.

A semi-transparent solar cell is represented by configuration 2, given in table 1. It is identical to configuration 1, but without the silver back contact. The model is used to find the absorption and transmission factor of this configuration and in figure 6 the results are shown. Compared to configuration 1, the short wavelength irradiance is equally well absorbed in the silicon wafer. For the long wavelength irradiance the transmission factor ($T_\lambda$) is close to 0.6. Assuming that the irradiance transmitted by the silicon wafer is completely absorbed by a second absorber, the overall absorption factor has increased to 84%.

The transmittance can be increased further by using a second AR-coating at the back silicon interface as is done in configuration 3.

It was found that if this coating is optimized for the long wavelength irradiance, the transmission factor reaches a maximum, which is also shown in figure 6. As a result of the second AR-coating, the overall absorption factor has increased even further to 87%.

Figure 6: The spectral absorption ($A_\lambda$) and transmission ($T_\lambda$) factors for configurations 2 and 3.

Strategy 2: Use of Improved Absorption in the Back Contact.

For standard solar cells a silver back contact is used because of its high reflectivity. This high reflectivity is not desirable for absorption of the long wavelength part of the spectrum. That is why simulations were performed using a different material as back metallization. Configuration 4 is identical to the standard solar cell of configuration 1, however the silver back contact is replaced by a platinum back contact. In figure 7 the results for configuration 4 are shown. When comparing these results with the results of configuration 1, it can be seen that the spectral absorption factor of the platinum back contact ($A_{Pt,\lambda}$) is significantly higher than for the silver back contact. As a result the overall absorption factor has increased to 82%.

By using a double-sided textured silicon wafer, a part of the long wavelength irradiance is trapped in the silicon and will reflect multiple times. During each reflection on the silicon-platinum interface, a part of the irradiance is absorbed by the platinum back contact. Configuration 5 was simulated to find out how large the influence of these multiple reflections is. This configuration is identical to configuration 4, but now both silicon interfaces are rough. To simulate the rough interfaces of configuration 5, a roughness parameter of 40 was used. With this value the experimental reflectance data of a textured silicon wafer (Burgers, 1997) can be fitted well.

In figure 7 the spectral absorption factor for configuration 5 is shown. It can be seen that the absorption of long wavelength irradiance in the platinum back contact has increased even further by using rough interfaces. The overall absorption factor increases from 82% to 85%. Note that it was assumed that rough interfaces reflect the same amount of irradiance as smooth interfaces. This is only true for relatively flat texture. It is expected that steeper texture absorbs even more irradiance. This will be investigated further.
CONCLUSIONS

A standard solar cell (configuration 1) has an absorption factor of 74%, which is significantly lower than the absorption factor of a black absorber used in a solar thermal collector, which is 95%. An optical model was developed to analyze how much the thermal absorption factor can be increased either at combi-panel level or at cell level.

Two possible strategies to increase the absorption factor were investigated. The first strategy is to use a second absorber behind a semi-transparent solar cell. If the transmittance of the solar cell for the long wavelength part of the spectrum is maximized, an overall absorption factor of 87% can be reached. If the strategy of increased absorption in the metallic back contact is applied, rough interfaces in combination with a platinum back contact give an absorption factor of 85%.

It is concluded that from a theoretical point of view both strategies are suitable to increase the long wavelength absorption factor significantly. This opens the route to realize PVT combi-panels with an overall efficiency approaching the thermal efficiency of a solar thermal collector.

AKNOWLEDGEMENTS

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NOMENCLATURE

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Subscripts

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REFERENCES


