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The AM1.5 absorption factor of thin-film solar cells

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ABSTRACT

Both for photovoltaic and photovoltaic/thermal applications insight is required in the mechanisms that determine the effective absorption factor A_{eff}. A_{eff} is the part of the incident irradiation that is converted into heat, taking into account that part of the energy is withdrawn as electricity. A_{eff} was studied for five different solar cell technologies using an optical simulation model and ranges from 74% for single junction amorphous silicon solar cells to 82% for CIGS solar cells. The simulations also show that the longer wavelength part of the spectrum is hardly absorbed by the active semiconductors, but mostly by free carrier absorption in the transparent conductive oxide film present in these devices.

1. Introduction

Not all parts of the solar spectrum are absorbed equally well by a solar cell. The light that is absorbed weakly can be trapped inside the solar cell and thereby travel a complicated optical path before being either absorbed, reflected or transmitted. This makes solar cells complex optical devices.

The main objective of the work presented here is to determine and compare the so-called AM1.5 absorption factor A of several types of thin-film solar cells. This factor is defined as the fraction of the incident solar irradiance that is being absorbed in the solar cell. It is the weighted average of the spectral absorption factor A_λ, i.e.

$$A = \frac{\int A_\lambda G_\lambda \, d\lambda}{\int G_\lambda \, d\lambda}, \tag{1}$$

where G_λ is the spectral power density of the AM1.5 solar spectrum. Because energy is conserved, all irradiance that is absorbed by the solar cell but not converted into electricity, is converted into heat. Therefore the effective absorption factor is defined as

$$A_{\mathrm{eff}} = A - \eta_{\mathrm{e}}, \tag{2}$$

where η_{e} is the electrical efficiency of the solar cell at Standard Test Conditions (STC, 1000 W/m^2 irradiance, AM1.5 spectrum, 25 °C cell temperature). A_{eff} represents the fraction of incident solar irradiance that is converted into heat. For crystalline silicon solar cells it was found that $A_{\mathrm{eff}} \approx 0.70$, i.e. as much as 70% of the incident solar irradiance is converted into heat [1]. A_{eff} has not been studied in sufficient detail for thin-film solar cells. This is related to the fact that an analysis for the entire solar spectrum is required to determine this quantity. So far, studies on the optics of thin-film solar cells were focused mainly on the part of the solar spectrum that can generate electricity, i.e. $0.3 < \lambda < 1.2\,\mu\mathrm{m}$.

Both for photovoltaic (PV) and photovoltaic/thermal (PVT) applications it is important to gain more insight in the absorption factor of thin-film solar cells. In PV applications, cells with *low* A_{eff} will have lower operational cell temperatures which is beneficial for their electrical yield. Solar cells are also applied in PVT applications. In a PVT collector a PV laminate generates electricity and functions as solar thermal absorber at the same time. In this way also the heat generated in the PV laminate can be extracted to be used effectively, e.g. for solar domestic water heating [2]. For PVT applications a *high* A_{eff} is desirable, because it will result in a higher thermal yield.

In this work we investigate the contribution of different wavelengths of the AM1.5 spectrum ($0.3 < \lambda < 4\,\mu\mathrm{m}$) to the A_{eff} of thin-film solar cells. First the model for the absorption factor of solar cells will be introduced. The model is then used to determine A_{eff} of various types of thin-film solar cell. In this work it is also investigated to which extent A_{eff} can be controlled by variation of the reflectance of the back surface reflector. Finally the conclusions are presented.

2. Optical model

Thin-film solar cells are multilayer optical systems. The layers in a thin-film solar cell could, for example, be glass, transparent conductive oxide (TCO), semiconductor (p, i and n layer) and a

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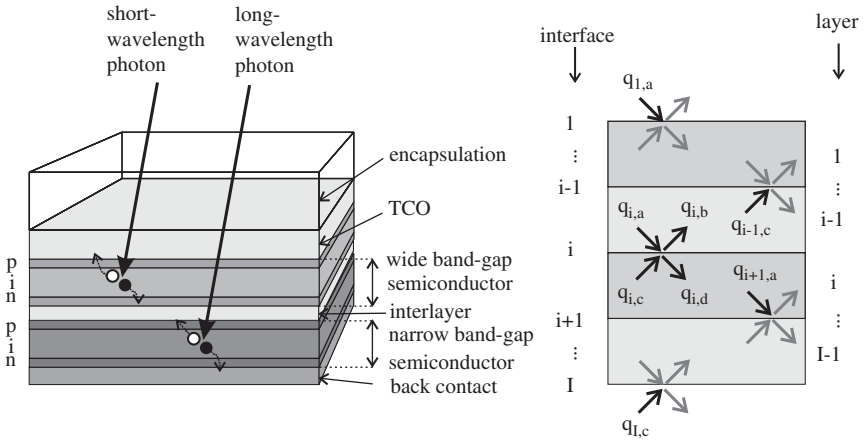

Fig. 1. Left: A schematic cross-section of a tandem thin-film solar cell. Right: Net-radiation fluxes indicated at each interface i of a multilayer system.

metal back surface reflector. Multi-junction solar cells consist of even more layers. The schematic structure of a tandem cell, having two semiconductor p-i-n structures, is illustrated in the left panel of Fig. 1. The optical constants of the individual layers can be derived from optical measurements and are known for most solar cell materials. This means that the laws of optics can be used to determine the reflectance r of each interface and the transmittance τ of each layer. The objective of the optical model presented here is to determine the spectral absorption factor A_λ of the multilayer system as a whole, taking into account the effects of light scattering.

2.1. Model description

To determine the spectral absorption factor, distinction has to be made between so-called coherent layers, with an optical thickness less than the coherence length of sunlight ($\approx 1\,\mu m$) and incoherent layers, with a larger optical thickness. A coherent layer gives rise to interference effects. Therefore the reflectance and transmittance of a coherent layer, or a stack of coherent layers, are calculated using a transfer-matrix method for electromagnetic waves [3]. A coherent layer or stack of coherent layers can then be represented by an interface characterised by a reflectance and a transmittance as defined by Macleod [3]. This simplifies the multilayer to an effective structure containing only incoherent layers.

Ray-tracing can be used to analyse light scattering [4] in the incoherent layers, but it is often more convenient to use the net-radiation method [5]. Instead of tracing many rays refracting and reflecting inside the multilayer system, four net-radiation fluxes are defined at each interface, as indicated in the right panel of Fig. 1. The interfaces are labelled $i = 1 \ldots I$, where I is the total number of interfaces. In the case of planar interfaces the relations between these fluxes are given by a set of $4I$ linear equations,

$$\begin{cases} q_{ia} = \tau_{(i-1)} q_{(i-1)d} \\ q_{ib} = r_i q_{ia} + t_i q_{ic} \\ q_{ic} = \tau_i q_{(i+1)b} \\ q_{id} = r_i q_{ic} + t_i q_{ia}, \end{cases} \tag{3}$$

where r_i is the reflectance of interface i, $t_i = 1 - r_i$. τ_i is the transmittance of layer i, defined by

$$\tau = \exp(-\alpha d/\cos\phi), \tag{4}$$

where α is the absorption coefficient and $d/\cos\phi$ is the distance a ray has travelled through the layer of thickness d with propagation angle ϕ. It is assumed that no irradiance is incident from below, i.e. $q_{Ic} = 0$. If the flux incident on the first interface q_{1a} is known, then the complete set of equations can be solved to determine all fluxes of every interface simultaneously. To solve the set of equations a Gauss elimination procedure is applied to the equations written in matrix-form. If the fluxes are normalised to have $q_{1a} = 1$, then the spectral absorption factor of layer i is given by

$$A_{\lambda,i} = q_{id} - q_{(i+1)a} + q_{(i+1)b} - q_{ic}. \tag{5}$$

The spectral absorption factor of the structure as a whole is then found by summing over all layers

$$A_\lambda = \sum_{i=1}^{I-1} A_{\lambda,i}. \tag{6}$$

Note that this spectral absorption factor is the absorption factor at a fixed wavelength λ. If the optical constants of one or multiple layers in the multilayer system are a function of λ, so will A_λ. Therefore to determine the AM1.5 weighted absorption factor A accurately, A_λ has to be determined in the entire wavelength range of the AM1.5 spectrum ($0.3 < \lambda < 4.0\,\mu m$).

The major limitation of the net-radiation method described above when applied to solar cells is that only *specular* reflection can be considered. Therefore the net-radiation method has been extended to incorporate the scattering of light at rough interfaces as well [1,6]. Note that these rough interfaces are commonly applied in solar cells to improve incoupling and to enhance light scattering. Optical models usually describe light scattering by rough interfaces in terms of an angular distribution function [7,8]. In the extended net-radiation method something similar is done, i.e. the angular range between 0° (surface normal direction) and 90° (surface parallel direction) is divided into angular intervals. Each flux q is divided into sub-fluxes, each corresponding to a different angular interval. The sub-fluxes are treated as elements of a flux vector, e.g. $\boldsymbol{q}_{1b} = (q^1_{1b}, q^2_{1b}, q^3_{1b}, \ldots)$. In this way the set of equations (see Eq. (3)) transforms into a set of matrix equations,

$$\begin{cases} \boldsymbol{q}_{ia} = \boldsymbol{\tau}_{(i-1)} \boldsymbol{q}_{(i-1)d} \\ \boldsymbol{q}_{ib} = \boldsymbol{r}_i^+ \boldsymbol{q}_{ia} + \boldsymbol{t}_i^- \boldsymbol{q}_{ic} \\ \boldsymbol{q}_{ic} = \boldsymbol{\tau}_i \boldsymbol{q}_{(i+1)b} \\ \boldsymbol{q}_{id} = \boldsymbol{r}_i^- \boldsymbol{q}_{ic} + \boldsymbol{t}_i^+ \boldsymbol{q}_{ia}, \end{cases} \tag{7}$$

where $\boldsymbol{\tau}$ is the layer transmission matrix and $\boldsymbol{r}$ and $\boldsymbol{t}$ are the scatter matrices, describing the angular distribution of scattered light for every angle of incidence. For example, element r_{ij} is the fraction of light incident from interval i that is scattered into interval j. To describe one interface completely, two scatter *reflection* matrices ($\boldsymbol{r}^+$ and $\boldsymbol{r}^-$) and two scatter *transmission*