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ScienceDirect

Energy Procedia 124 (2017) 240–249

Energy Procedia

www.elsevier.com/locate/procedia

7th International Conference on Silicon Photovoltaics, SiliconPV 2017

Combining ray tracing with device modeling to evaluate experiments for an optical analysis of crystalline Si solar cells and modules

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Abstract

This paper develops a procedure to analyse the optical losses of both crystalline Si cells in air and of modules in an industrial environment. We evaluate EQE and reflectance (R) measurements on the cell, and R measurements on various spots of the module by combining the recently developed module ray tracer from PV Lighthouse with established Sentaurus device modeling. The IQE is the product of absorptance (A_{eh}) in Si due to e-h pair generation and their collection efficiency (η_{col}). With Sentaurus device modeling of our PERC cells, we can model η_{col} to high precision and compute A_{eh} from the IQE. At long wavelengths, this A_{eh} allows us to quantify light trapping in both the cell in air and the cell in the module without fitting internal reflectance etc. At short wavelengths, the parasitic absorptance A_{par} in the front SiN_x layer is precisely evaluated with ellipsometry, photothermal deflection spectroscopy (PDS), and ray tracing. In the module, we reproduce the R measurements with the ray tracer and obtain R at the backsheet and the ribbon by iteration and evaluate their Lambertian factor by consistency. The ray tracing model, based on these measurements and with the achieved consistencies, then gives us an optical loss analysis of all parts of the cell and the module and allows us to evaluate possible improvements to high precision.

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Peer review by the scientific conference committee of SiliconPV 2017 under responsibility of PSE AG.
10.1016/j.egypro.2017.09.269

Keywords: ray tracing; device simulation; crystalline Si solar cells; loss analysis

1. Introduction

In an industrial environment, an optical analysis of Si cells and modules is performed:

- to monitor whether the antireflection coatings (ARC) on the cells is optimum;
- to assess the light trapping properties of the cells in the module;
- to assess the optical losses in the module, particularly due to the front reflectance, the front and back metallization, the gaps between the cells, and at the edge of the module;
- to predict potential optical improvements, serving as a quantitative foundation for decision making on where and how the module can be improved with economic benefit.

For an experimental foundation of an optical loss analysis, reflectivity (R), quantum efficiency (QE) and ellipsometry measurements of optical layers (their refractive index n and extinction coefficient k) are commonly used. The difficulties in these measurements include the following:

- R is either measured in an area containing front metal fingers, so the reflectivity and scattering of the metal need to be subtracted [1], or R is measured in a very small area between front metal fingers, so it needs to be confirmed that this small area is representative for the whole cell.
- QE is a mixture of both optical and electrical transport processes. Procedures to distinguish between the two [2-4] face the difficulty that one of them needs to be either very precisely known or needs to be assumed or fitted in a self-consistent procedure. Additionally, the QE may depend on bias illumination [5, 6].
- Ellipsometry does not measure n and k directly, but infers these values [7] by e.g. setting optical resonances with selectable strength and wavelength in a model consistent with the Kramers-Kronig (KK) relations, or using a wavelength-by-wavelength approach, which is generally not consistent with the KK relations [8]. Particularly the first approach limits the precision of k in SiN_x at short wavelengths. Alternatively, n and k can be inferred from R and T measurements in so-called backward calculations (as opposed to forward calculations where R, T and A are calculated from n and k) using various analytical approximations to various circumstances [9-13].

Our paper aims at reducing the uncertainties due to these difficulties while keeping the optical analysis sufficiently simple for an industrial environment. Various papers with a similar aim have been published including a combination of ray tracing and measurements [14-24], or a recent notable example is measuring J_{sc} of the module instead of R [25].

Our paper takes advantage of two main modeling tools: first, the recently developed module ray tracer (MRT) of PV Lighthouse [18,26], which rapidly solves the reflection, transmission and absorption in each material of a PV cell or module. Second, the semiconductor device software Sentaurus [27], which is capable of precisely simulating the electrical transport processes that affect the QE because a detailed Sentaurus model is used anyway for improving cells [28], as a roadmapping tool [29], and as a tool to analyse efficiency distributions and their origins in mass production [30,31]. Our main approach is basically as follows:

1. The measured R is corrected for the front metallization.
2. The corrected R is reproduced by ray tracing using ellipsometry data and literature data for n and k. With this, the parasitic absorptance A_{par} in the front ARC is obtained. As in Refs. [16,32], the internal quantum efficiency is then calculated from the measured external one using the equation IQE = EQE/(1–R–A_{par}). Other analyses in the literature often neglect A_{par} [33-35] and may underestimate the IQE at short wavelengths and η_{col} of the emitter (see point 3). Hence, we carefully measure k of the front ARC with ellipsometry [7] and compare it to photothermal deflection spectroscopy (PDS) [36,37] measurements.
3. In most cases [38], the IQE is the product of absorptance in Si due to e-h pair generation A_{eh} and the carrier collection efficiency η_{col}: IQE = $A_{eh}\eta_{col}$. At short wavelengths, A_{eh} = 1, so IQE = η_{col} is solely determined by the emitter. Having achieved consistency between the measured R and the raytraced R, we gain insight into the electric properties of the emitter in unprecedented detail.