Solar Energy Materials & Solar Cells 123 (2014) 17–29

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Accurate opto-electrical modeling of multi-crystalline silicon wafer-based solar cells

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ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form
23 October 2013
Accepted 13 December 2013
Available online 21 January 2014

Keywords:
Opto-electical modeling
Multi-crystalline silicon
Wafer-based solar cells

ABSTRACT

Modeling of multi-crystalline silicon solar cells has been recently widely used for fast and cost-effective performance improvements. The optimization of device performance requires deep understanding of the opto-electrical losses in a fabricated solar cell. To carry out trustworthy simulations for performance analysis and optimization, the simulation program has to be calibrated to the performance of the fabricated device. In this article an accurate opto-electrical modeling of multi-crystalline silicon solar cells is presented. Specific issues that arose during the calibration process were addressed, such as the optical model describing light scattering due to wafer texturing, the electrical modeling of heavily doped emitter and the opto-electrical modeling of the back surface field. Calibrated model parameters, obtained from theory or measurements, led to an excellent simultaneous matching between simulated and measured reflectance spectrum, internal and external quantum efficiencies and dark and illuminated current–voltage characteristics of the multi-crystalline silicon solar cells. In addition, opto-electrical losses in the investigated solar cells were determined and quantified.

1. Introduction

The structure of highly efficient solar cells based on crystalline silicon (c-Si) is a complex opto-electrical system. To enhance the absorption in the bulk region of the silicon wafer and thus increasing the short-circuit current density (J_{SC}), several light management techniques are employed at the same time. Anti-reflective coatings, surface textures for light scattering at both the front and rear side and efficient back reflectors can be typically found in nowadays' solar cells. In addition, to improve the collection of photo-generated carriers and thus increasing the open circuit voltage (V_{OC}) and the fill factor (*FF*), the bulk region is sandwiched between the (selective) emitter at the front side and the back surface field (BSF) region at the rear side combined with front and back passivation layers [1]. Hence, for integrated analysis and optimization of the opto-electrical performance of this complex device, computer modeling has become an extremely important tool [2]. Due to doping concentration profiles in the emitter and BSF that vary over many orders of magnitude in thin regions the computer model must use Fermi-Dirac statistics in order to properly describe the behavior of such degenerate layers [3].

In this work we present (i) a detailed opto-electrical model based on the Advanced Semiconductor Analysis (ASA) program [4] of an industrial multi-crystalline silicon (mc-Si) solar cell that was used as a reference and (ii) the analysis of opto-electrical losses of these devices. Special care was devoted to the assignment of proper values to the input parameters of the numerical model. This step is known as *calibration* of model parameters [5–7]. Generally a calibration process consists of tuning a number of input parameters until a good matching between measured and simulated characteristics of the reference solar cell is achieved. Despite the simplicity of this approach, it must be noted that the extracted values of input parameters might not be unique or represent realistic values. To avoid this situation, we used as starting values those predicted by theory or experimentally determined. In particular, for proper modeling of anti-reflective effect and light trapping in mc-Si solar cells, the morphological analysis together with the measurements of optical properties of the device were carried out. In order to realistically represent the front emitter, the mechanisms of electrical recombination were investigated and the values of fitting parameters such as surface velocity recombination (SVR) and minority carrier lifetime were compared with those predicted by the theory. In case of the bulk silicon, the electrical recombination in the bulk and at the rear side of the solar cell was described by using the effective minority carrier diffusion length extracted from the measured internal quantum efficiency (*IQE*) of the reference device. Finally, focusing on the rear side, the back reflectance was described with optical properties of Si–Al alloy and scattering parameters, while

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http://dx.doi.org/10.1016/j.solmat.2013.12.019

recombination losses were also modeled in terms of the effective minority carrier diffusion length.

Using the parameters of our calibrated opto-electrical model, the simulated reflectance spectrum (R), the internal and external quantum efficiencies (EQE) and (iii) the dark and illuminated current–voltage characteristics (J–V) characteristic simultaneously matched very well the measured curves of a commercial reference mc-Si solar cell. Furthermore, the opto-electrical losses in all supporting layers of the reference solar cell were determined and quantified. Our calibrated model can be applied to simulate all c-Si based solar cells.

2. Overview of the opto-electrical device simulators for C–Si solar cells

Numerical modeling has been widely applied to c-Si solar cells both by academic institutions and industry. Commercially available software programs like ATLAS [8], SENTAURUS [9,10], and MICROTECH [11] are the most common software programs used by the photovoltaic (PV) industry. However, specific physical models may be absent in these commercial software programs or have to be adapted. For these reasons, many research groups have developed their own advanced physical models describing processes in solar cells that are not implemented yet in commercial computer programs.

For simulating the electrical operation of c-Si wafer-based solar cells, it is sufficient to solve the two-carrier time-dependent semiconductor transport equations in one dimension. In 1960s, Gummel from Bell Laboratories introduced an iterative method to solve this set of equations [12]. Since then, several models based on his numerical approach were developed and applied to Si wafer-based solar cells. Around 10 years later, a numerical code was written and used at Bell Laboratories to investigate and design solar cells with conversion efficiency higher than 20% [13,14]. In 1980s, the SCAP1D software was developed at Purdue University. This software program was later extended into two dimensions and enabled to simulate a broad variety of solar cell structures such as interdigitated back contact solar cells [15,16]. In mid-1980s, a one-dimensional (1-D) semiconductor simulator called PC-1D [17] was developed as free-available software. In contrast with most of the device simulators at the time, it solved the equations not using the finite difference method but the finite element method. This software, broadly used by the PV community, has strongly contributed to the progress in design of highly efficient c-Si solar cells [18,19]. Recently, the PC-1D software has been used together with the optical modeling of the so-called isotexture [20] to simulate the opto-electrical behavior of mc-Si solar cells [21].

The AFORSHET software, developed at Helmholtz Centre in Berlin, has been mainly used for simulating hetero-junction silicon-based solar cells [22]. The DESSIS software was used at University of New South Wales in Sydney to analyze c-Si solar cells. Simulation results were employed to realize a solar cell with a record efficiency of 24.7% in 1994 [23–25] and to optimize the design of a solar cell on a 47 μm thick float-zone c-Si wafer with record efficiency of 21.5% [26]. In 2011 the PV Lighthouse website was launched. The web site offers online free calculators that simulate various aspects of solar cell operation [27].

The abovementioned software programs are mainly suited for analysis and optimization of the electrical performance of solar cells. The trend in PV industry towards the use of fewer raw materials demands the development and application of advanced light management techniques in order to maximize light absorption in thinner c-Si wafers. This trend also requires that modeling can correctly handle optical processes such as scattering, diffraction and plasmonic absorption using textured surfaces in c-Si solar cells. Since typical c-Si solar cells accommodate textures whose features are much larger than the incident wavelengths, ray tracing approach is widely employed to calculate the optical properties of c-Si solar cells. The most frequent models rayn [28], texture [29], sunrays [30], raysim [31], sonne [32] and recently introduced daidalos [33] or crowm [34] are three dimensional (3-D). To incorporate optical results of 3-D models into a 1-D device simulator, the 3-D generation profile $G(x,y,z)$ is usually averaged in a 1-D generation profile $G(z)$ which describes the optical situation inside the device along its depth [7]. Recently, better light in-coupling and light scattering triggered by textures with smaller-than-wavelength features are being implemented also in c-Si wafer solar cells [35]. In this case, both coherent non-scattered (i.e. specular) and incoherent scattered (i.e. diffused) light inside the device must be considered [36]. Examples of optical simulators that take into account both specular and scattered light propagation are optical models from École Polytechnique Palaiseau [37], sunshine program from Ljubljana University [38], GENPRO3 optical module implemented in the ASA program of Delft University of Technology [39] and the Prague optical model [40].

The ASA program was developed and used at Delft University of Technology to simulate thin-film amorphous Si solar cells. For this purpose advanced models for describing the properties of the amorphous silicon were implemented in this program. Later the ASA program was extended with the models that enabled the program to simulate c-Si solar cells. In this contribution we demonstrate that the optical and electronic models that are implemented in the ASA program can be used for simulating state-of-the-art mc-Si solar cells fabricated with industrial-scale processes.

2.1. The ASA device simulator

The ASA program is a 1-D device simulator that integrates both optical and electrical simulations for the complete modeling of solar cell operation. From optical point of view, solar cells are multi-layered optical systems with flat and/or textured interfaces. Since all practical c-Si solar cells use textured surfaces, modeling must take into account refraction and scattering at these surfaces in order to calculate the absorption profile accurately. In case of scattering, an optical model has to take into account both coherent and incoherent light propagation throughout the simulated device [38]. The optical model GENPRO3 implemented in the ASA program fulfils this requirement and, in addition to wavelength-dependent complex refractive indices of individual layers, uses as input descriptive scattering parameters of a rough interface, like haze and angular intensity distribution (AID) [41]. Simulating a solar cell with the ASA program, optical outputs are the R spectrum, the absorptance spectrum (A) in each layer of the multi-layered structure and the generation rate related to the optical absorption profile. Once the generation rate is determined, it is used as an input for the electrical simulations.

The electrical part of the ASA device simulator is based on semiconductor equations and includes, among other models, Shockley–Read–Hall (SRH) and Auger recombination-generation rates as well as the Fermi–Dirac statistics. Particularly, the dependence of carriers mobility, diffusion lengths, band-gap narrowing and minority-carrier lifetime on the doping densities of donors (N_D) and acceptors (N_A) is included. The steady state operation of homo-junction semiconductor device is described by a set of coupled differential equations which, in general, cannot be solved analytically. In the ASA program, this set of equations is solved by means of numerical methods. The free electron concentration, n, the hole concentration, p, and the electrostatic potential, ψ, are used as variables. After reading structure-statements from an input file, the ASA engine (i) generates a grid along the depth of the device, (ii) carries out the spectral absorption rate and the