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An effective medium approach for modeling polycrystalline silicon thin film solar cells

Ana-Maria Teodoreanu [a,b,*], Caspar Leendertz [c], Tobias Sontheimer [c], Lars Korte [c], Bernd Rech [c]

[a] Technische Universität Berlin, Department of Semiconductor Devices, Einsteinufer 19, 10587 Berlin, Germany
[b] PVcomB, Competence Centre Thin-Film and Nanotechnology for Photovoltaics Berlin, Schwarzschildstr. 3, 12489 Berlin, Germany
[c] Institute for Silicon Photovoltaics, Helmholtz Zentrum Berlin füuer Materialien und Energie, Kekuléstrasse 5, 12489 Berlin, Germany

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ABSTRACT

A simple and fast 1D effective medium simulation model for polycrystalline silicon thin film solar cells was defined, by using the device simulator AFORS-HET. The model was calibrated with current–voltage measurements of solar cells under illumination and in t he dark. The experimentally determined variation of the solar cell characteristics with varying absorber doping and absorber thickness can be reproduced by the model. Through inverse modeling, the effective defect density in the absorber layer was determined and it was shown that the open circuit voltage V_{OC} of the cell is limited by defects localized in the bulk of the absorber layer. Using the calibrated simulation model for sensitivity analyses, different optimization strategies for this type of solar cells have been assessed. Firstly, the optimum absorber thickness as a function of absorber doping and defect densities has been determined and secondly, the V_{OC}−increase when using a layer of hydrogenated amorphous silicon (a-Si:H) to form a heterojunction back surface field has been simulated as a function of the absorber defect density.

1. Introduction

Polycrystalline silicon (poly-Si) thin film solar cells have high potential for being cost-effective candidates among the solar cell production technologies as they combine the advantages of thin film technology with the good material quality of crystalline silicon (c-Si), the know-how of the semiconductor devices industry and the natural abundance of silicon [1].

There are several methods to prepare poly-Si thin film solar cells [2–6]. In this study we focus on cells obtained by electron-beam (e-beam) evaporation of hydrogenated amorphous silicon (a-Si:H) layers on a planar glass substrate and a subsequent solid phase crystallization (SPC). This method is environmentally friendly in comparison to the standard chemical vapor deposition (CVD) methods, as it uses no hazardous gases. Moreover, higher deposition rates can be attained with this method. Also, the quality of the material achieved by e-beam deposition on planar substrates is equivalent to that of plasma enhanced CVD (PECVD) deposited material, reaching an efficiency of up to 7.8% on 35 cm^2 minimodules [7].

However, the efficiency of poly-Si thin film solar cells can further be improved [9]. In order to achieve this, two approaches can be used: the first requires to improve the quality of the material in order to increase the V_{OC} of the cell, whereas the second requires to improve the light trapping in the thin film layer by using rough substrates for deposition, in order to increase the short circuit current J_{SC}. While efforts on J_{SC} improvement have already been successful [10], improving the V_{OC} is still a challenge for poly-Si thin film solar cells which we will tackle with our present work.

To this end, we developed a simple and fast, well-calibrated 1D effective medium simulation model for poly-Si thin film solar cells in order to identify the efficiency-limiting parameters of these cells. The model was calibrated by comparison to illuminated and dark current–voltage (J–V) curves. Further, the calibrated model is used to find optimization strategies for the poly-Si thin film solar cells.

2. Experimental details

2.1. Solar cell samples

For the calibration of the solar cell model (see Section 3.3), 10 poly-Si thin film minimodules with varying absorber doping concentrations and varying absorber thicknesses were used.

* Corresponding author at: Technische Universität Berlin, Department of Semiconductor Devices, Einsteinufer 19, 10587 Berlin, Germany.
Tel.: +49 30 314 29895; fax: +49 30 314 29761.
E-mail address: ana-maria.teodoreanu@tu-berlin.de (A.-M. Teodoreanu).

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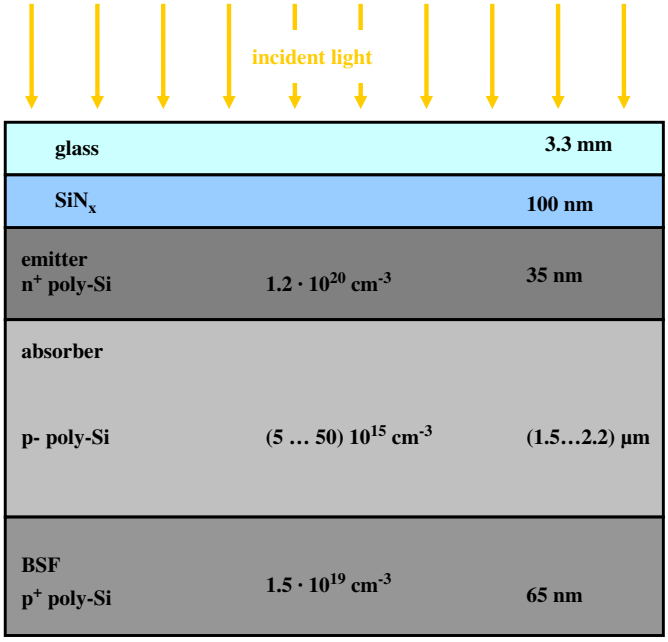

Fig. 1. Structure of the poly-Si thin film solar cell, not to scale. The type of each layer, the doping in cm^{-3} and the layer thickness are specified.

A minimodule consists of 12 solar cells in superstrate configuration which are monolithically contacted in series. The layers were deposited as amorphous films, and subsequently crystallized. As substrate for the deposition a planar SiN_x coated Schott Borofloat glass with a PECVD-deposited n^+−type a-Si:H emitter, provided by CSG Solar Pty Ltd, was used. The deposition of the p^-−type a-Si absorber and p^+−type a-Si back surface field (BSF) was performed at HZB by e-beam evaporation. For the absorber deposition two deposition rates of 300 nm/min and 600 nm/min were used. The a-Si:H layer stack was subsequently crystallized in an SPC process at 600 °C and further exposed to rapid thermal annealing (RTA) [11,12] followed by hydrogen passivation (HP) [13,14]. The application of a white resin layer as diffuse back reflector and the contacting using a rear point contact metallization scheme were performed by CSG Solar Pty Ltd [15].

A schematic structure of the poly-Si thin film solar cell is shown in Fig. 1. The layer doping concentration and thickness are specified on the corresponding layers. The emitter doping is 1.2×10^{20} cm^{-3} and the emitter thickness 35 nm. The absorber doping varies from 5×10^{15} cm^{-3} to 5×10^{16} cm^{-3} and the absorber thickness varies from 1.5 µm to 2.2 µm. The BSF doping is 1.5×10^{19} cm^{-3} and the BSF thickness 65 nm.

The absorber and BSF doping were achieved by adjusting the temperature of a boron effusion cell, the substrate temperature and the deposition rate during the e-beam deposition process and were calibrated in advance by secondary ion mass spectroscopy (SIMS) measurements. The absorber layer thicknesses were measured and calibrated by profilometer measurements, and the emitter and BSF thicknesses by single-wavelength-ellipsometry.

The manufacturing processes and the performance of the minimodules are presented and discussed in detail in [16].

2.2. J–V measurement

The J–V curves of the minimodules described in Section 2.1 were measured with a sun simulator equipped with a metal halide lamp, which has a $<95\%$ homogeneity of the standard irradiance on the minimodule area of 34.63 cm^2. The measurements have been performed at standard testing conditions: AM1.5 spectrum, 100 mW/cm^2 irradiance and 25 °C.

3. 1D model for the poly-Si thin film solar cell

For creating a model of the poly-Si thin film solar cells we use the device simulator AFORS-HET [18]. This simulator numerically solves the system of coupled continuity and Poisson equations for charge carrier densities of electrons and holes and the electric potential. Using the interrelations of these three parameters with other solar cell parameters, one can perform a variety of simulations of measurements [18], which can be used for inverse modeling and sensitivity analyses. In our case, we simulate the dark and light J–V curves of the solar cells.

3.1. Assumptions and input parameters for the 1D simulation

The input parameters for the model are material and cell parameters which are measured values, values based on the literature, or free model parameters. These parameters will be defined in the following in conjunction with the assumptions made for a 1D simulation.

The simulated solar cells consist of a c-Si layer stack which is identical to the poly-Si cell structure in Fig. 1: an n^+−type emitter, a p^-−type absorber and a p^+−type BSF. For the SiN_x on Borofloat glass stack, the measured spectral reflection and spectral transmission are specified.

We assume for the poly-Si layers material parameters of c-Si, which are homogeneously distributed over the bulk of the layers. The assumption of c-Si parameters is justified by the grain size which significantly exceeds the layer thickness resulting in a columnar structure of the poly-Si grains [19]. Due to this columnar structure the transport of the charge carriers to the contacts is parallel to the grain boundary. Thus, in a first approximation, the charge carriers do not cross any grain boundary and the vertical mobility determines the charge carrier transport.

For the thickness and the doping concentration of the layers we used the values specified in Section 2.1.

We further use a single defect in the middle of the bandgap, homogeneously distributed throughout the layer, and with equal capture cross-sections for electrons and holes of $\sigma_n = \sigma_p = 10^{-14}$ cm^2. These capture cross-sections are typical values for c-Si [20]. As demonstrated by Fehr et al. [8], deep defects prevail in the grain interior of SPC poly-Si material and are performance-limiting for the solar cells. This finding thus supports the use of an effective defect density which is homogeneously distributed in the layers.

The effective defect density of the absorber layer N_{eff} is a free parameter in our model, which will be determined by inverse modeling. It will be shown later in Section 3.2 that there is a different signature regarding their influence on the illuminated and dark J–V curves for defects localized in the volume N_{eff} than for defects localized at the interface D_{it}. Therefore, we use only a volume defect density in the absorber layer N_{eff} as a model parameter without including interface defects. Further, the effective defect density of the emitter and BSF layers were set to a constant value of 10^{19} cm^{-3}. With this defect density the shape of external quantum efficiency measurements in the short and long wavelength range can be reproduced in simulation. However, the J–V characteristics, on which we focus in our study, are not sensitive to this parameter.

The shunt resistance R_P and the series resistance R_S of the external circuit are free parameters in our model and will be determined by inverse modeling.

The surface recombination velocity (SRV) at the metallic contacts is 10^7 cm/s.

We further use a simple model for light trapping: for the 1D simulation of the generation rate the Lambert–Beer law is used and an internal reflection at the front surface of the cell $R_{int,front}$ and at the back side $R_{int,back}$ of the cell are considered. These two factors include