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Suppression of interface recombination by buffer layer for back contacted silicon heterojunction solar cells

Miroslav Mikolášek*, Patrik Príbytný, Daniel Donoval, Juraj Marek, Aleš Chvála, Marián Molnár, Jaroslav Kováč

Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Electronics and Photonics, Ilkovičova 3, 812 19 Bratislava, Slovakia

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ABSTRACT

Back contacted heterojunction solar cell consisting of an n-type amorphous silicon emitter and p-type crystalline silicon wafer with an N^+ buffer layer inserted at the interface has been studied with particular emphasis on the role of interface recombination. We show that by optimization of the N^+ buffer layer the charge distribution at the heterointerface can be modified to achieve a lower sensitivity of the output performance on the defect states at the interface. This significantly reduces requirements for optimization of the silicon heterojunction solar cells in term of heterointerface quality and passivation layer thickness. Simulation results emphasize the necessity to optimize the back contact arrangement simultaneously with doping of the N^+ buffer layer to achieve a high output performance of the solar cell.

1. Introduction

The main goal of the photovoltaic industry is to reach high performance and low fabrication costs of solar cells at the same time. Silicon heterojunction solar cells (SHJ) consisting of amorphous silicon and crystalline silicon forming a heterojunction (a-Si:H/c-Si) have prospects to fulfill this goal and thus have became the subject of extensive study in recent time [1–3]. The low fabrication costs of SHJ cells stems from the low temperature deposition of the amorphous emitter giving a significant lower temperature budget. This opens the opportunity for using a silicon substrate with a thickness below 100 μm without the problem of wafer bow which usually originates due to the thermal stress. The thinner silicon substrate brings material savings and thus a further decrease in the solar cell price.

The presence of the heterojunction between crystalline (c-Si) and amorphous silicon (a-Si:H) gives rise to band discontinuity at the interface and results in a higher diffusion voltage (V_D) for SHJ compared to silicon solar cells with a homojunction. This is reflected in the higher open-circuit voltage (V_{OC}) and consequently a high conversion efficiency (η). The perspective to attain a high performance of SHJ has already been demonstrated by the PANASONIC (former group SANYO), which has achieved the conversion efficiency of 24.7% on an n-type silicon substrate with a thickness of 98 μm [4] on their patented HIT (heterojunction with intrinsic thin layer) structure. The HIT structure contains a thin layer of intrinsic amorphous silicon (a-Si:H(i)) inserted at the a-Si:H/c-Si heterointerface with the function to passivate the crystalline silicon substrate and thus provide low defect states at the heterointerface. Based on these excellent results novel concepts with contacts placed at the bottom of the substrate have become a new trend in SHJ solar cells development. Having both contacts at the non-illuminated side of the solar cell eliminates the contact shading and brings a higher short-circuit current (J_{SC}). The arrangement of the back contacts to achieve effective separation of photogenerated carriers without worsening of the fill factor (FF) emerged as a new challenge for optimization of back contacted solar cells [5,6]. Due to this, large-area efficiency of 24.2% [7] obtained with back contacted silicon heterojunction solar cells (BC-SHJ) is slightly lower compared to front contact SHJ cells.

To fully utilize the potential of SHJ and BC-SJH solar cells, the study and optimization of emitter amorphous silicon/crystalline silicon heterointerface with focus on recombination was identified as the most important issue [8–10]. V_D and hence also V_{OC} strongly depend on the charge distribution at the heterointerface. The low defect states density at the interface, which guarantees

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* Corresponding author. Tel.: +421 2 60291872; fax: +421 2 65423480.
E-mail address: miroslav.mikolasek@stuba.sk (M. Mikolášek).

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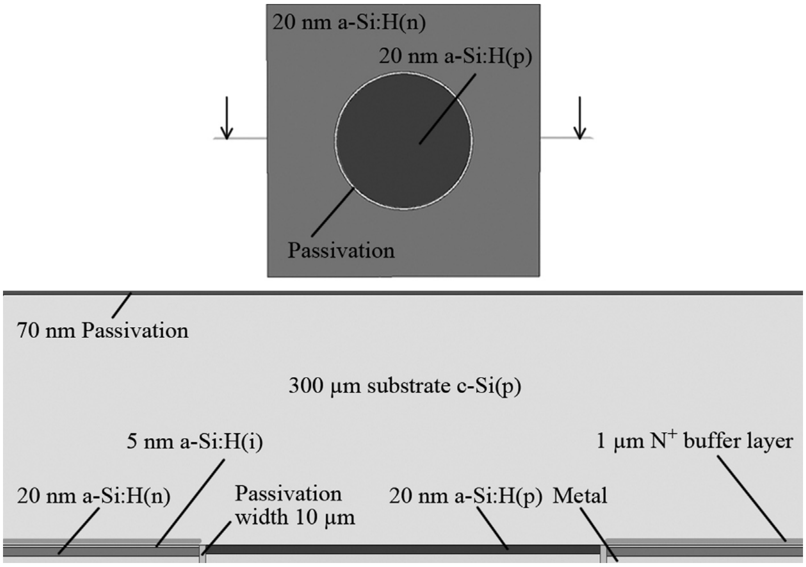

Fig. 1. Bottom view and cross-section of the simulated structure of BC-SHJ with N$^+$ buffer layer. The rear a-Si:H(p) p-contact is a point contact surrounded by an a-Si:H(n) emitter.

strong carrier inversion and thus low recombination at the heterointerface, is the main technological challenge for achieving high V_{OC} and thus high performance of SJH solar cells. In this paper we present a two-dimensional (2D) simulation study of BC-SJH on p-type substrate with an incorporated N$^+$ buffer layer in the emitter structure. The simulation study is done with intention to show possible compensation of the negative effect of defect states at the heterointerface and to attain a low sensitivity of V_{OC} on the interface quality. Optimization of the solar cell is discussed in terms of different back contact arrangements. Results are compared with a solar cell without the N$^+$ buffer layer.

2. Simulation set-up

The 2D numerical simulation study of BC-SHJ solar cell was carried out by Synopsys TCAD “Sentaurus Device” [5,11], which brings more accurate results than conventionally performing 1D simulations. It is extensively used for modeling of (opto-)electronic devices, and it is well suitable for solar cells modeling [12]. Comparison of SHJ solar cell results obtained by Synopsys with results obtained by automat for simulation of heterostructures [13] reveals very good agreement [14]. This demonstrate applicability of Synopsys software also for simulation of heterojunction solar cells based on silicon. Sentaurus Device calculates the optical generation rate in the solar cell and couples it with the electrical simulation. Several methods for computing the optical generation rate are implemented in Sentaurus Device. In our simulations, the TMM (transfer matrix method) solver was used to compute the polarization-dependent optical intensity and optical generation rate inside the solar cell. To calculate the polarization-dependent reflectance, transmittance and absorbance of the solar cell, the properties of incident light (wavelength, intensity, angle of incidence, polarization) and of the semiconductor layer (complex refractive index and quantum yield) were considered.

The bottom view and cross-section of the solar cell structure with the N$^+$ buffer layer used in our simulations are shown in Fig. 1. The a-Si:H(p) p-contact is formed as a point contact and the a-Si:H(n) emitter represents the area around this point contact. The a-Si:H(n)/c-Si(p) emitter interface is passivated by a 5 nm thick layer of a-Si:H(i). A 1 μm thick N$^+$ buffer layer is formed in the silicon substrate of the emitter interface. Thus the layer sequence of the emitter structure is as follows: a-Si:H(n)/a-Si:H(i)/c-Si(N$^+$)/c-Si(p). In the sequel this emitter structure is labeled as a-Si:H(n)/c-Si(p) for simplicity reasons. The results obtained on BC-SHJ with N$^+$ buffer layer were compared with an identical structure without the N$^+$ buffer layer. In the simulated model of both structures a 300 μm thick p-type crystalline silicon (c-Si) wafer with concentration $\sim 10^{15}$ cm^{-3} is passivated with Si_3N_4 (70 nm) at the front surface. The electron and hole lifetimes for c-Si are 1 ms. The rear a-Si:H(p) p-contact and a-Si:H(n) emitter n-contact are placed at the bottom of the wafer, both with thicknesses of 20 nm. For a-Si:H layers, the critical parameters such as the band gap, doping (conductivity), energy distribution of the exponential band tails, and the Gaussian distribution of mid-gap dangling bonds states are chosen based on reference [11,15] and tuned to fit the measured optoelectronic properties of the deposited a-Si:H layers. Parameters of the model are listed in Table 1. The conduction band offset of 0.15 eV and defect states density of 10^{12} cm^{-2} were set as default values at the a-Si:H(n)/c-Si(p) interface. In the simulation, these parameters were varied to investigate the impact of the heterointerface properties on the output performance. While the study is focused on the suppression of the recombination at the emitter interface, the a-Si:H(p)/c-Si(p) contact properties were modeled as ideal without defect states.

The default width of the p-point contact is 0.6 mm. The default distance between two p-contacts is 0.62 mm. The area between the p-contacts represents the emitter, which is isolated from the p-contact by the isolation gap with a width of 10 μm. In the simulation, the width of the p-contact was fixed and the area of the emitter contact was changed. In this way variation of the emitter contact fraction was achieved defined as:

$$f_E = \frac{A_E}{A} \qquad (1)$$

where A is the whole area of the solar cell and A_E is the contact area of the emitter n-contact. f_E was varied in the simulation in the range from 26% to 91%. For the structure with default contact arrangement the value of f_E was 75%.

Three basic semiconductor equations were solved—the Poisson equation, electron and hole continuity equations together with the drift–diffusion model Auger and Shockley–Read–Hall recombinations were also taken into account for the crystalline silicon wafer. For a-Si:H(n)/c-Si(p) emitter heterointerface a thermionic emission

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