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Modeling and optimization study of industrial n-type high-efficiency back-contact back-junction silicon solar cells

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ABSTRACT

The knowledge of the loss mechanisms in industrial back-contact back-junction (BC BJ) silicon solar cells and their dependence on geometrical and substrate parameters provides the opportunity to further increase the cell efficiency of this cell type. In the presented paper the influences of the different loss mechanisms on the cell parameters of BC BJ solar cells were analyzed. The basis of the simulations was an advanced 1-d model that regards the detrimental influences of intrinsic losses, optical losses, series resistance losses and recombination losses on the cell efficiency. In this context the main influence of electrical shading losses will be discussed in particular, due to the restrictions of the minimum base width as a result of industrial structuring processes. The predictions of the theoretical calculations will be compared with the measured cell parameters of BC BJ solar cells for various cell designs.

In order to further improve the cell design the influences of geometrical parameters (pitch, base width) and substrate parameters (base resistivity) on the cell efficiency will be analyzed. The modeling data show that the optimum cell geometry defines a balance between series resistance and electrical shading losses.

1. Introduction

One of the main research topics in the field of silicon photovoltaics is the development of high-efficiency silicon solar cells. There are several different cell concepts, such as the PERL [1] solar cell, that assure cell efficiencies greater than 20%. However the requirements of local structuring techniques for most of the high-efficiency solar cell concepts lead to very high production costs. Therefore, one of the biggest challenges is the fabrication of high-efficiency silicon solar cells with low-cost structuring techniques. Sunpower Corp. showed in 2007 that it is possible to reach average cell efficiencies of up to 22% [2] in mass production with a back-contact back-junction (BC BJ) silicon solar cell structure. In the BC BJ solar cell structure the emitter and the back surface field (BSF) dopings are both located in an interdigitated structure on the back side of the solar cell. Thus, both metallization grids are also located at the back side of the cell shown in Fig. 1. The BC BJ solar cell has many advantages, such as the avoidance of optical shading losses at the front side metallizations. Therefore, this cell type has an increased absorption and short circuit current density. Another advantage is the possibility of wide emitter and base metallization fingers at the back side of the cell to reduce the series resistance of the metal contacts.

Several authors [3–8] have developed modeling approaches for BC BJ solar cells. Swanson [3] derived an analytical approach for concentrator point-contact solar cells with a pitch of about 45 μm, which was extended by Sinton and Swanson [8] with numerical descriptions of the bulk generation and recombination effects. Dicker et al. [4] developed a two-dimensional numerical model for one sun BC BJ solar cells, which describes especially the optical carrier generation, the losses due to a distributed metal series resistance and the perimeter losses. Furthermore, there were several publications about 2-d [5,6] and 3-d [7] modeling approaches using the numerical simulator Sentaurus Device [9] (formerly DESSIS).

This work presents an approach to determine the influences of the different loss mechanisms on the cell parameters of one sun BC BJ solar cells processed with industry relevant technologies. The model describes the detrimental effects of intrinsic losses, optical losses, recombination losses and series resistance losses. In order to analyze the effects of different loss mechanisms on the *J–V* characteristic, the model will contain different parameters which are related to specific loss mechanism in the cell. Furthermore, the derived model will be used to determine the influence of different cell design parameters on the cell efficiency, in order to optimize the cell design of an industrial one sun BC BJ solar cell. The predicted cell parameters (cell efficiency, fill factor,

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short circuit current density and open-circuit voltage) and the modeled J–V characteristic will be compared to several measurements of BC BJ solar cells fabricated at Fraunhofer ISE. The cell structure and the process sequence of the analyzed BC BJ solar cells have been described by Granek et al. [10]. The solar cells were fabricated with FZ n-type silicon and were processed with industrially feasible structuring techniques, such as screen printing of resist masks and laser processing, without the use of any photolithography step. Therefore, the pitch of the cells is limited by the use of low-cost structuring techniques and is in the range of 1300–3500 μm with a constant base width of 600 μm. The large pitch leads to increased values of pitch-related loss mechanisms, such as series resistance [10] or electrical shading losses [11,12]. The aim of this paper is to find a modeling approach that identifies and quantifies the loss mechanisms of industrial BC BJ solar cells and to evaluate the modeled results with characterization measurements. Furthermore, the modeling results for varying cell design parameters provide the opportunity to further improve the cell efficiency of this cell type.

2. Modeling and characterization

In order to optimize the cell design of a BC BJ solar cell it is important to analyze and quantify the influences of the different loss mechanisms on the solar cell parameters and determine their correlation to specific cell parameters, such as the pitch or the choice of the substrate. Hence the following modeling section is focused on three goals: in the beginning, it is important to determine the upper boundaries of the cell parameters due to intrinsic limitations. In the second step, a modular composited model of a BC BJ solar cell will be presented that allows a differentiation between the diverse effects of the loss mechanisms on the cell parameters. The last step is the determination of the unknown modeling parameters in the developed model and the verification of the modeled results with measured values of the fabricated BC BJ solar cells.

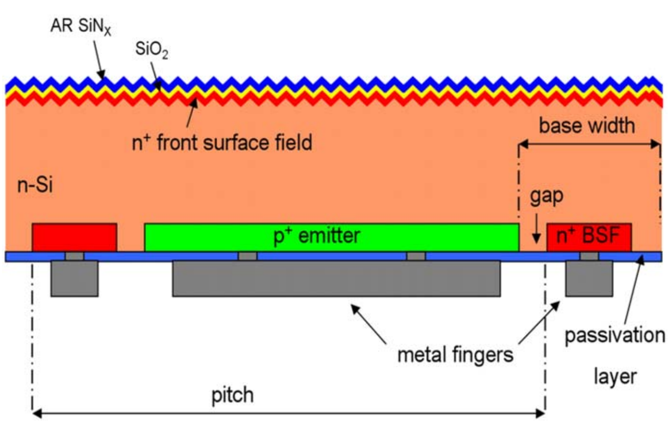

Fig. 1. Schematic cross-section of a highly efficient n-type back-contact back-junction silicon solar cell analyzed in this work. The pitch is the sum of emitter width and the base width (consisting of BSF and gap widths) and is two times the size of one symmetry element of this structure.

2.1. Intrinsic limitations

The maximum cell efficiency of a silicon solar cell is limited by various intrinsic loss mechanisms. The upper boundary of the cell efficiency is caused by thermodynamic limitations [13], the fixed band-gap energy of silicon [14,15], the finite geometrical light trapping [15,16] and the intrinsic recombination processes [17–19]. The efficiency limit of a one-sun silicon solar cell is calculated to be around 29% [20]. However, the exact value depends on the specific cell design, due to the dependency of the intrinsic short circuit current density on the cell thickness [15,16] and the dependency of the intrinsic recombination rate on the base doping density and cell thickness. Hence the J–V curve of an intrinsic silicon solar cell can be described by Eq. (1)

$$J_{\text{int}}(V) = J_{sc,int}(W) - qWR_{\text{int}}(V, W, N_D) \tag{1}$$

where $J_{sc,\text{int}}$ is the intrinsic short circuit current density [16], q is the elementary charge, W is the cell thickness, N_D is the base doping density and R_{int} is the parameterized intrinsic recombination rate given by Kerr et al. [17–19], including radiative and Auger recombination in the bulk. Modeling of the intrinsic cell efficiency of an n-type silicon solar cell by Eq. (1) leads to values in the range 27.5–29.5% for wafer thicknesses of 50–500 μm and base resistivities of 0.5–100 Ω cm. Table 1 shows exemplarily the intrinsic limitations of the cell parameters for an n-type silicon solar cell with cell thickness of 150 μm and base resistivity of 1 and 8 Ω cm. The intrinsic limitations of a solar cell are the upper boundaries of the cell parameters and give the maximum attainable cell efficiency for one specific cell thickness and base doping density.

2.2. Modeling of BC BJ solar cells

Eq. (2) shows an advanced 1-diode model that can be used to describe the characteristic of a J–V curve of a BC BJ solar cell

$$J(V) = J_{sc} - qWR_{\text{int}}(V - JR_s(V)) - J_0(V - JR_s(V))\left(e^{\frac{qV - qJR_s(V)}{k_BT}} - 1\right) \tag{2}$$

where J_{sc} is the short circuit current density, $J_0(V)$ is the saturation current density of the non-intrinsic recombination mechanisms, R_s is the total series resistance of the solar cell in Ω cm^2, J is the current density of the solar cell, k_B is the Boltzmann constant and T is the temperature. In order to quantify the influence of the different loss mechanisms on the cell parameters of a BC BJ solar cell, it is necessary to determine the three unknown parameters of Eq. (2)—the short circuit current density J_{sc}, the non-intrinsic saturation current density J_0 and the series resistance R_s. In the following sections there will be modeling approaches to determine these unknown parameters. Table 2 shows the applied modeling parameters for the following simulations. The sheet resistance of the emitter in Table 2 equals the value of the processed solar cells and is normally used as a BSF doping profile for p-type solar cells. Thus, it is not optimized for the use as a

Table 1
Intrinsic limitations of an n-type silicon solar cell with cell thickness of 150 μm and base resistivity of 1 and 8 Ω cm

Cell parameter	Intrinsic limitation (ρ_{Base}=1 Ω cm)	Intrinsic limitation (ρ_{Base}=8 Ω cm)
Cell efficiency	η_{int}=28.3%	η_{int}=28.5%
Fill factor	FF$_{\text{int}}$=86.5%	FF$_{\text{int}}$=86.9%
Short circuit current density	$J_{sc,\text{int}}$=44.0mA/cm^2	$J_{sc,\text{int}}$=44.0 mA/cm^2
Open-circuit voltage	$V_{oc,\text{int}}$=743mV	$V_{oc,\text{int}}$=746 mV