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Loss analysis and efficiency potential of p-type MWT–PERC solar cells

Benjamin Thaidigsmann*, Johannes Greulich, Elmar Lohmüller, Simon Schmeißer, Florian Clement, Andreas Wolf, Daniel Biro, Ralf Preu

Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany

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ABSTRACT

A loss analysis is carried out for monocrystalline large-area p-type metal wrap through passivated emitter and rear cells (MWT–PERC) with thermal SiO_2/SiN_x surface passivation reaching a maximum conversion efficiency of 20.6%. Analytical and numerical device modelling identifies the most important loss mechanisms and allows for a separation of the different series resistance contributions and various short circuit current loss mechanisms. Based on the extracted data, an estimation of the possible maximum conversion efficiency for p-type MWT–PERC solar cells is given.

1. Introduction

Metal wrap through solar cells [1] with aluminium back surface field (MWT–BSF) are currently being transferred into industrial scale production, successful pilot line production has already been demonstrated [2–4]. Analogous to H-pattern solar cells, the implementation of rear surface passivation into MWT structures leads to an increase in conversion efficiency. For the resulting MWT–PERC structure efficiency values exceeding 20% have been reported for monocrystalline p-type silicon material [5]. This paper aims to give an estimation of the maximum achievable efficiency of such p-type MWT–PERC devices. Relevant loss mechanisms such as shading, non-optimal light trapping, series resistance and recombinative losses are investigated and quantified. Analytical and numerical device modelling based on experimentally determined cell properties allows for an identification of promising approaches for future improvements of the MWT–PERC structure. Despite the fact that the loss analysis is carried out for MWT solar cells, most of the findings are similarly valid for high efficiency H-pattern PERC devices.

2. Approach

Highly efficient MWT–PERC-type solar cells fabricated from float-zone silicon (FZ-Si) and Czochralski-grown silicon (Cz-Si) with a laser-doped selective emitter structure and thermal SiO_2-based surface passivation [5] (see Fig. 1) represent the starting point of the investigation. An in-depth characterisation forms the basis for analytical and numerical device modelling and allows for the calculation of the impact of each loss mechanism on cell performance.

Table 1 shows the measured current–voltage parameters for the cells investigated in this paper. All cells feature a thick thermally grown SiO_2 layer as rear side passivation and a thin SiO_2 layer as a front side passivation. On either side, a PECVD SiN_x covers the SiO_2 layer. Two different technologies for front contact formation are investigated—screen printing and dispensing [6] of the silver grid lines. In the case of dispensing, the MWT structure offers the particular advantage that no busbar and therefore no second printing step is necessary.

3. Device characterisation and loss analysis

3.1. Short circuit current

As various loss mechanisms interfere with each other, a specification of absolute loss values for the short circuit current and particularly a summation of the different losses is hardly possible. Therefore, only the expected gain in short circuit current density after deactivation of each single loss mechanism will be given in this section. Relevant optical loss mechanisms are shading by the front grid, reflexion at the front surface and non-optimal light trapping. Electrical losses are caused by a reduction of the collection probability due to recombination in the emitter (including front surface), in the base and at the rear surface.

Shading of the front side directly translates into a loss in short circuit current. Conventional H-pattern solar cells with screen printed contacts typically show ~7% front side shading. By applying the MWT concept, this value is reduced to 4.1% (cell 3) as no busbars are present on the front side. With the more advanced dispensing approach, the width of the grid lines decreases from ~90 μm down to ~60 μm while the aspect ratio

* Corresponding author. Tel.: +49 761 4588 5045.
E-mail address: benjamin.thaidigsmann@ise.fraunhofer.de (B. Thaidigsmann).

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is increased from ~0.3 to ~0.9. Due to the circular shape of the dispensed lines, the effective optical width is further reduced by ~30% [7] resulting in 2.3% shading for cells 1 and 2 with a line spacing of 1.8 mm. Additionally, considering improved alignment possibilities, the width of the selective emitter area is reduced from 180 μm for the screen printed grid (cell 3) to 100 μm for cell 1 and 2 with dispensed grid lines. A characterisation of reference samples with full-area laser-doped emitter enables the determination of the current loss due to reduced blue-response of the highly doped areas [8]. The illuminated highly doped areas of the cells with dispensed front grid account for a loss in j_{SC} of ~0.1 mA/cm^2 whereas ~0.2 mA/cm^2 are calculated for the wider laser-doped lines of the screen printed grid.

All remaining optical and electrical losses are accessible via quantum efficiency (QE) analysis [9]. For the sake of clarity, only data for cell 1 (Cz-Si, dispensed front contact) is presented exemplary in the following. Fig. 2(a) shows the relevant QE and reflectance curves.

The reduction of j_{SC} due to reflexion at the front surface is given by the equation:

$$\Delta j_{SC,\,R_{Si,front}} = \int_{300\text{ nm}}^{1200\text{ nm}} IQE(\lambda) q \phi_{AM1.5\text{ G}}(\lambda)(1-M) R_{Si,front}(\lambda) d\lambda \qquad (1)$$

where M denotes the shaded area fraction, $\phi_{AM1.5\text{ G}}$ is the solar spectrum and q is the elementary charge. The front surface reflectance $R_{Si,front}$ is the linear extrapolation of the reflectance R_{Si} in between the grid lines [10] to wavelengths above 950 nm, a linear fit is performed in the range from 900 to 950 nm.

The loss in j_{SC} due to free carrier absorption (FCA) [11] and non-optimal light trapping is calculated with a similar integration,

$$\Delta j_{SC\text{ opt},i} = \int_{300\text{ nm}}^{1200\text{ nm}} q \phi_{AM1.5\text{ G}}(\lambda)(1-M) IQE(\lambda) l_{opt,i}(\lambda) d\lambda. \qquad (2)$$

Here, $l_{opt,i}$ indicates the optical losses in IQE, $i \in$ {FCA, parasitic absorption, escape}. It is important to note that losses due to FCA and parasitic absorption $l_{opt,\{FCA,\ parasitic\ absorption\}}$ have to be weighted with the reflectance R_{Si} prior to integration. As free carrier absorption, escape reflectance and parasitic absorption at the rear surface strongly interfere with each other and the IQE itself, the values calculated with Eq. (2) are only a rough estimation. Losses due to emitter, bulk and rear surface recombination are calculated by

$$\Delta j_{SC\text{ rec},i} = \int_{300\text{ nm}}^{1200\text{ nm}} q \phi_{AM1.5\text{ G}}(\lambda)(1-M)(1-R_{Si}(\lambda)) l_{rec,i}(\lambda) d\lambda \qquad (3)$$

with $i \in$ {emitter, bulk, rear}.

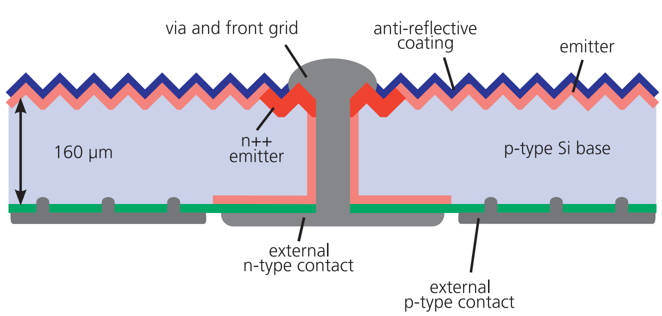

Fig. 1. Structure of the monocrystalline p-type MWT–PERC solar cells analysed in this paper. The front side features a selective emitter structure, the screen printed rear contact is locally connected to the base via laser fired contacts. Front and rear are passivated by thermally grown silicon oxide.

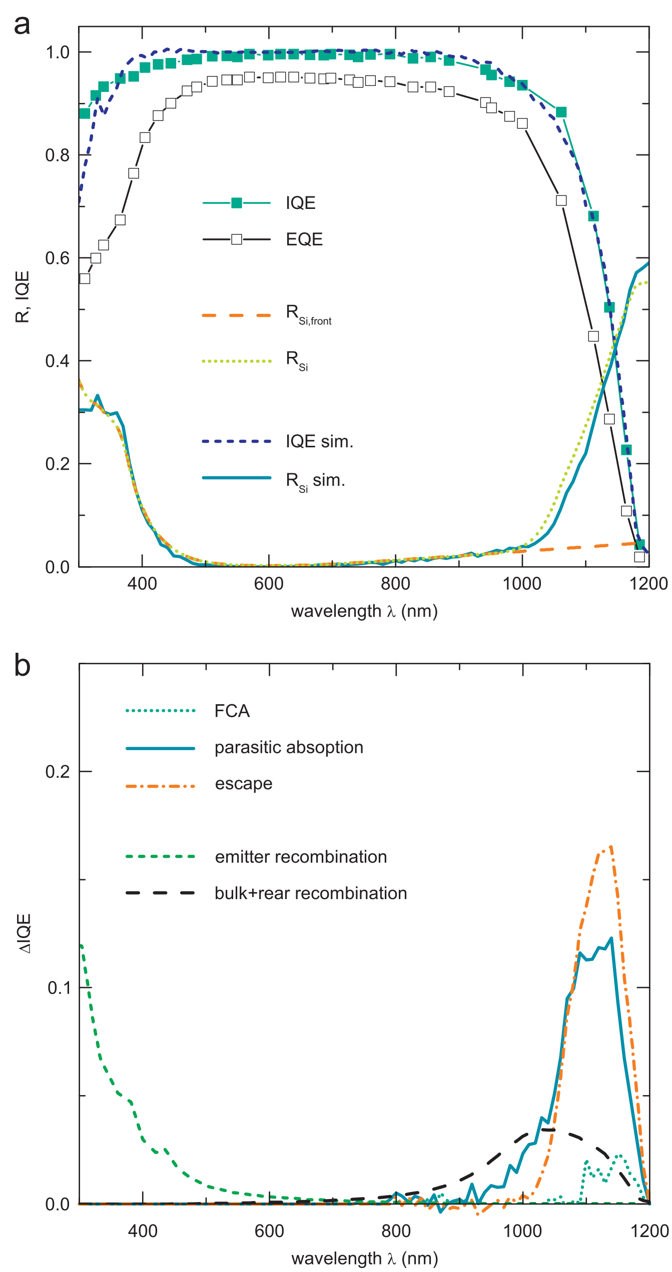

Fig. 2. (a) Measured and simulated QE and reflectance data for cell 1 (Cz-Si, dispensed front grid). (b) Wavelength dependent IQE losses for cell 1.

Table 1
I–V parameters of three MWT–PERC-type solar cells [5] for standard test conditions measured by Fraunhofer ISE CalLab (except *pFF* which is measured with an industrial cell tester). Cell area: 149 cm^2; cell thickness: 160 μm. *Hotplate annealing at 200 °C for 20 min.

Cell no.	Base material	Base resistivity (Ω cm)	Front contact	V_{OC} (mV)	j_{SC} (mA/cm^2)	FF (%)	$pFF-FF$ (%)	η (%)
1	Cz-Si (annealed*)	1.8	Dispensed	651	40.3	76.6	5.9	20.1
2	FZ-Si	0.5	Dispensed	661	39.9	78.3	4.7	20.6
3	FZ-Si	0.5	Screen-printed	658	39.0	78.4	4.8	20.1