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Simulation-based efficiency gain analysis of 21.2%-efficient screen-printed PERC solar cells

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Abstract

Passivated Emitter and Rear Cells (PERC) with efficiencies well above 20% are likely to become the next mass production technology. A quantification of all power loss mechanisms of such industrial PERC cells is helpful in prioritizing future efficiency improvement measures. We report on a numerical simulation of the power losses of a 21.2 %-efficient industrial PERC cell using extensive experimental input data. Our synergetic efficiency gain analysis relies on deactivating single power loss mechanisms in the simulation at a time to access the full potential power gain related to that mechanism. The complete analysis therefore explains the efficiency gap between the industrial PERC solar cell and the theoretical maximum efficiency of a crystalline Si solar cell. Based on the simulations, the largest single loss mechanism is front grid shadowing followed by recombination in the emitter and its surface. All individual resistive losses, all individual optical losses and all (avoidable) individual recombination losses sum up to efficiency gains of 0.8%, 1.6%, and 1.3 %, respectively, which is 3.7% in total. The efficiency gap between real and ideal solar cell is, however, much larger with 7.3%. The discrepancy is mainly due to the non-linear behaviour of recombination-based power losses which adds synergetic efficiency enhancements.

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Keywords: PERC solar cells; screen-printing; device simulation; power loss analysis

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1. Introduction

As the best industrial-type Passivated Emitter and Rear Cells (PERC) achieve efficiencies of 21% and beyond [1,2,3], a quantification of the impact of all power loss mechanisms is required to ensure that future technological improvements reduce the dominating losses and hence provide a high efficiency improvement. The Free Energy Loss Analysis (FELA) [4] frequently used in solar cell analysis accounts for electrical power losses and represents those as free energy dissipation rates. Therefore the total extracted power P of a solar cell is the free energy generation rate $\dot{F}_g$ minus the free energy dissipation rates caused by recombination $\dot{F}_r$, and transport of charge carriers $\dot{F}_t$:

$$P = \dot{F}_g - \dot{F}_r - \dot{F}_t.$$

For a given working point of a solar cell, one is now able to calculate for example the power loss $\dot{F}_r$ for a specific recombination channel. However, the potential in power gain by improving that recombination channel is higher than $\dot{F}_r$ since avoiding this loss will simultaneously increase the generated free energy

$$\dot{F}_g = \int_V dV \, (E_{FC} - E_{FV}) g$$

where g is the generation rate in the cell volume V and $E_{FC} - E_{FV}$ denotes the splitting of the quasi-Fermi level of electrons and holes. The increase of free energy generation is noted by the experimentalist primarily as an increase of the solar cell's open circuit voltage V_{oc} and thus also by change of the working point V_{mpp}. Another approach to power loss analysis [5] uses analytic expressions to calculate the current losses by recombination and imperfect optics. In order to acquire the power losses these current losses are multiplied with the internal voltage of the solar cell at the maximum power point (mpp). This approach, as well as the FELA, does not account for the shift of the working point that goes along with avoiding a loss. Correspondingly the calculated power losses underestimate the potential in power gain and will not add up to the theoretical limit of around 29%. To access the full potential power gains ΔP of each power loss mechanism, we apply the synergetic efficiency gain analysis (SEGA) [6] to our 21.2%-efficient industrial PERC solar cell [2]. The SEGA explains the efficiency gap between the cell under investigation and an ideal cell. It treats optical, electrical and resistive losses on an equal footing and makes these different losses directly comparable.

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2. Numerical model

We model our 21.2%-efficient dual-printed 5 busbar (5BB) PERC solar cell (labeled "group 3" in Ref. 2) which is schematically shown in Fig. 1a) by a 3-step simulation sequence. Raytracing of a textured solar cell with SUNRAYS [7] generates a 1-dimensional photogeneration profile. This profile is then used in a 2D Sentaurus device [8] simulation of a PERC solar cell with a non-textured planar front surface. The unit cell is sketched in Fig. 1b). Finally, the I-V curve resulting from the Sentaurus simulation is used for a grid simulation with LTSpice IV [9] to include resistive losses of front fingers and busbars. All simulations apply realistic input parameters that are either measured on test structures or are taken from the literature.