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# Surface recombination parameters of interdigitated-back-contact silicon solar cells obtained by modeling luminescence images

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ABSTRACT

Current losses at surfaces play a crucial role in the optimization of high-efficiency silicon solar cells. We present a new approach to characterize the surface recombination activity of interdigitated-back-contact (IBC) silicon solar cells by comparing experimental and simulated photoluminescence images (PL). The different recombination properties of the p- and n-doped regions of IBC cells in combination with the operating condition lead to contrast profiles in the PL image that vary with bias voltage. We achieve a good matching of experimental and simulated data for the investigated cells enabling the analysis of how sensitive the simulated contrast patterns are to changes in the surface recombination at the emitter, back- and front-surface-field and if a better matching of the experimental PL images is possible. Using these PL images in combination with simulations around the open circuit voltage $V_{oc}$ the determination of surface recombination velocities $S$ and emitter saturation currents $J_0$ on finished cells is made possible for the first time. This approach also opens a new path towards loss analysis of finished PERL, PERC, MWT and other silicon solar cells.



## 1. Introduction

The interdigitated-back-contact (IBC) solar cell concept has already proven median cell efficiencies beyond 23.5% at an industrial level [1] and great efforts are put in increasing its efficiency. In order to further push cell efficiencies, spatially resolved characterization techniques such as PL-imaging can be of great help. PL-imaging has previously been used to visualize qualitative improvements in recombination activity [2] for IBC solar cells and concepts for a quantitative analysis have been proposed [3]. In recent years, photo- and electroluminescence-imaging (PL/EL) has been used on conventional Al-BSF industrial silicon solar cells. Current applications include imaging local defects from the cell production, obtaining spatially resolved cell parameters such as series-resistances, dark saturation current densities [4–7]. Recently, promising attempts of cell parameter imaging of all conventional parameters in the two-diode model have been presented [8]. All of these methods assume that each pixel in the camera image corresponds to one independent diode in the bulk, where the current flows vertically. However, this assumption is not valid for IBC cells due to the two-dimensional doping structure and predominantly lateral current flows. Therefore, these methods cannot be directly applied to IBC cells and spatially resolved cell parameter imaging has not yet been shown.

To further increase IBC cell efficiencies, both the dark-saturation-current densities ($J_0$) and the surface recombination velocities (SRVs), are critical for short-circuit current density ($J_{sc}$) and open-circuit voltage ($V_{oc}$). Currently, values for dark saturation currents ($J_0$) and surface recombination velocities ($S$-value or SRV) are commonly determined via special lifetime samples in a Kane–Swanson experiment for which test structures produced in a preceding experiment or in parallel to the regular solar cells are required [9]. These samples consist of thin, lowly-doped and high-purity float-zone silicon wafers where one or both wafer surfaces are doped with the specific doping profile for the cells. The evaluation of (quasi-steady-state) photo-conductance measurements (QSSPC) yields $J_0$ for the distinctive doping profile.

The error of $J_0$ is difficult to estimate and depends on the sample and the used models [10,11]. Also, creating lifetimes samples that experience all the temperature steps as a regular metallized solar cell would, are time consuming and present additional costs. Also, the metal–semiconductor interface cannot be imitated for a conventional lifetime sample. Therefore, the final $J_0$ of the cell might not be the same as those obtained from the lifetime samples. Furthermore, the recombination activity of silicon-metal interfaces cannot be measured with the QSSPC approach but would require a quasi-steady-state PL (QSSPL) measurement [12,13].

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In this work, we introduce a new method to address local surface recombination activity through a combination of experimental luminescence imaging and numerical modeling. We demonstrate that the profiles of photoluminescence intensity can be modeled with a promising agreement between experiment and simulation, using the measured $J_0$ for each cell region and the SRVs at the physical surfaces ($S_0$) extracted from the simulation tool EDNA [14]. By improving the matching between experiment and simulation, we learn how the cell's actual surface recombination is compared to the one expected from lifetime samples. At the same time, we learn how $J_0$ of locally doped regions influences the cell's performance, especially $V_{oc}$ and how the source of these losses can be traced by the specific luminescence signature with a good estimation of the actual local $J_0$ of individual cells.

## 2. Experimental data

### 2.1. Cell structure and technology

The $2\times 2\,cm^2$ IBC solar cells presented in this work were fabricated on n-type float-zone Si with a resistivity of 1 Ω cm, and a thickness of 180 μm. The minority-carrier bulk lifetime is about 3.3 ms. Fig. 2(a) depicts a schematic of the cross-section, (b) an on-scale schematic of the rear side diffusions and (c) a photograph of the cell's rear side.

At the rear side, the 1600 μm wide B-diffused emitter and the 300 μm wide P-diffused back-surface-field (BSF) are separated by a 150 μm wide $Al_2O_3$-passivated gap, resulting in a 2200 μm pitch. The front side has a random pyramid surface texture, a homogeneous P-diffused front-surface-field (FSF) and a $SiO_2$–$SiN_x$ stack which serves as passivation and anti-reflection coating. All masking steps were performed with photolithography. The emitter, BSF and FSF diffusions have peak dopings of $1\times 10^{19}\,cm^{-3}$, $6\times 10^{19}\,cm^{-3}$ and $1\times 10^{19}\,cm^{-3}$ respectively, with junctions depths of about 1.5 μm, 0.3 μm and 0.3 μm, respectively.

Table 1 summarizes the $J_0$ and $S_0$ for each region, as evaluated with the help of lifetime test samples by QSSPC measurements assuming Richter's model for Auger-recombination [15] at 300 K.

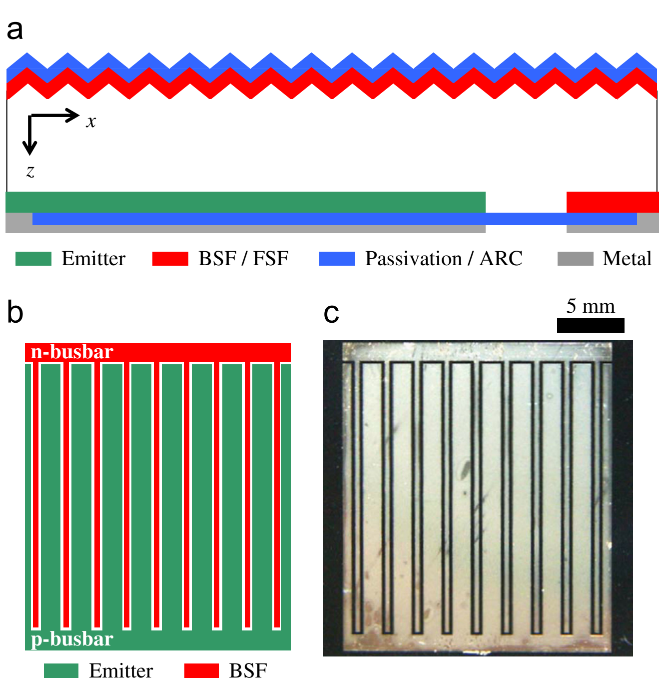


**Fig. 1.** (a) Cross-section schematic of the IBC cell, (b) backside doping schematic and (c) photograph of the rear side.

The $S_0$ of the contact areas are estimations. $J_0$ for each region was calculated for 300 K using the intrinsic carrier-density $n_{i0}$ of $9.65\,cm^{-3}$ [16]. The $S_0$ that correlates with the measured $J_0$ are extracted using the freeware tool EDNA by McIntosh et al. [14] with an update that includes Richter's Auger-recombination model. Using an AM1.5G spectrum and measured at 26.85 °C (300 K), the cell showed a $J_{sc}$ of 39.7 mA $cm^{-2}$, a $V_{oc}$ of 680 mV, a fill factor (FF) of 76.8% resulting in an efficiency of 20.7%. All results shown in this work are at 300 K because the material parameters for simulations have been determined at accurately 300 K. The increased temperature compared to STC conditions (25 °C) decreases the $V_{oc}$ by 2–3 mV.

### 2.2. Experimental setup

The experimental PL setup for this work consists of a cooled 1 MP Silicon CCD camera, a spatially homogenous excitation light source at 1 sun equivalent AM1.5 intensity by a 790 nm diode laser, a bipolar power source, a temperature-controlled measurement chuck and a stack of optical filters between the camera and the sample. For all presented measurements we used a filter stack beginning at the sample side with a 1000 nm dielectric short-pass filter, followed by a 976 nm dielectric- and a 950 nm nanoparticle long-pass filters. The long-pass filters block reflected laser light, while a short-pass filter reduces light-smearing due to point-spread of photons in the Silicon CCD chip [17,18]. The use of a 1000 nm short-pass filter strongly facilitates the evaluation process, as it reduces the effect of image blurring [19]. This comes at the cost of increased exposure times and higher background noise, which had to be taken care of. The camera was set to focus on the surface of the cell and the aperture of the IR-optimized lens was decreased until no further increase in sharpness could be detected. This ensures a compromise between exposure time and image resolutions. The spatial resolution was about 40 μm per camera pixel. Technical details on a very similar luminescence setup can be found in [20].

### 2.3. Interpretation of experimental luminescence images

Before simulating luminescence images, we comment on some of the qualitative phenomena observed in experimental luminescence images of IBC cells. Fig. 2 depicts pseudo-color photoluminescence images at different applied voltages.

Under short-circuit conditions (a) most of the carriers generated by light are extracted; hence the overall intensity of the luminescence signal is low. We observe an increased luminescence coming from above the BSF region. This is a manifestation of a decreased collection efficiency of minority charge carriers relative to the region above the emitter due to the longer distances that carriers need to overcome by diffusion [21]. This is a common phenomenon of IBC cells sometimes called “electrical shading”, which has been studied in detail elsewhere, particularly through light-beam-induced-current measurements [22–24].

At 680 mV (d), which is the cell's $V_{oc}$, virtually no current flows out of the cell. Therefore, the generated charge carriers diffuse through the bulk material until they recombine. Since the bulk of the material and the FSF are very homogenous, the contrast patterns come from relative differences between the surface recombination activity between emitter, BSF, gap and the contact areas. At $V_{oc}$, the BSF regions show lower PL intensity than the emitter regions and thus lower charge carrier densities are detected, which reflect increased Shockley–Read–Hall (SRH) and Auger recombination. An increased total recombination of a doped region at $V_{oc}$ conditions as represented by the respective $J_0$, should lead to lower carrier densities and a lower PL intensity. We conclude from (d) that the BSF area has a stronger recombination

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