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Loss analysis for laser separated solar cells

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Abstract

Half-cell modules are promising candidates for new innovative module designs as they offer major advantages. Modified connection schemes reduce the serial resistance losses yielding a higher overall module performance. The reduced size of the cells allows a more flexible module design that is needed for special applications such as implementations on curved surface. Furthermore, a better performance under partial shading can be achieved. However, these advantages lead to a benefit only if the losses induced by the cell separation process are negligible. In this work, we study the different sources of power reduction, i.e. increased shunting and recombination, for mono-crystalline and multi-crystalline silicon solar cells separated using different laser process parameters. It is shown that recombination plays the major role for an optimized laser separation process. Additionally we identify the laser scribing process as the major source of losses in comparison to the mechanical breaking.

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Keywords: laser; solar cells; loss analysis; electrical characterization

1. Introduction and motivation

It is well known that the series resistance losses of a PV-module can be reduced by implementing half-cells instead of full cells. While the series resistance contribution of the individual cells remains unchanged the losses in the connectors are reduced [1, 2, 3]. This can lead to an increased module performance of about $1\%_{rel} - 3\%_{rel}$. However, the cell separation process induces an additional process step accompanied by additional costs. Hence, half-cell modules will become a competitive alternative only if the cell separation process is performed such that the additionally induced electrical cell losses and mechanical damages are minimized [4].

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There are several cell-splitting technologies which are applicable to separate a full-cell into two half-cells. Among those, the laser scribing with subsequent mechanical breaking of the cells is rather cost efficient and results in small and controllable edge damages. Splitting a full-cell into half-cells leads to two additional sources of electrical cell losses. First, additional shunts along the new edge might be induced due to the laser treatment. These shunts are visible in the current-voltage characteristic as a decreased parallel resistance. Alternatively, lock-in-thermography can be employed to localize these shunts. Second, the additional surface of the new edge might lead to an increased carrier recombination. This is reflected as a change in the second saturation current, i.e. the J_{02} recombination contribution in the two diode model.

In this work, a number of batches of multi-Si and mono-Si solar cells has been prepared and separated into half-cells using laser scribing and mechanical breaking. The cells have been electrically characterized before the laser process, after the laser process and after the final cell separation. The cell parameters of the two-diode model that have been extracted from the current-voltage data indicate the quantitative contribution of the two major loss sources. We show that for an optimized laser separation process, it is not the shunting but the recombination that leads to the major losses. Furthermore, it is shown that the relative change in efficiency that is caused by the cell separation is similar for mono-crystalline cells and multi-crystalline cells. Finally, our results indicate that the laser scribing imposes a larger damage to the cell than the breaking. Therefore, the optimization of the laser process is a crucial step in the development of an industrial half-cell process.

2. Sample preparation and measurement approach

In our first experiment, we have compared two different cell types: multi-crystalline silicon solar cells and mono-crystalline silicon solar cells. We have analyzed commercially available cells from a mass production process. Two batches of 20 cells each have been selected for each cell type. Each of these batches has then been processed with an optimized laser process such that the damage due to the laser is minimal. On the other hand, the laser scribing has to be deep enough to ensure a clean breakage in the subsequent mechanical separation. For all experiments we used pulsed laser irradiation with a wavelength of 532 nm and pulse length of 10 ns. The pulse energy was about 230 μJ. Optimal results were obtained with a scribing speed of 15 mm/s. Scribing was done twice to reach the necessary scribe depth of about one third of the cell thickness.

All cells have been electrically characterized on a solar simulator before and after the cell separation. The cells were electrically contacted using 48 current pins and 3 voltage pins. The current-voltage-curves where analyzed and the two-diode-model parameters extracted. The focus of this first experiment has been on the identification of the major loss mechanism, i.e. decreasing R_p or increasing J_{02}, and on the comparison of mono- and multi-crystalline silicon cells. While the shunt resistance R_p has been obtained from the slope of the dark-I-V-curve at zero voltage the loss current J_{02} is determined by analyzing the I_{sc}-V_{oc}-curve.

Fig. 1: Full cell before laser scribing (left), full cell after laser scribing and before breaking (middle), and two half cells positioned on the measurement stage (right).

In our second experiment, the two individual steps of the cell separation, i.e. laser scribing and mechanical breaking, were investigated in more detail. Two batches of five solar cells have been prepared. The first batch has been subject to the cell separation. While leaving laser wavelength, pulse duration, and energy unchanged a modified scribing speed of 40 mm/s was used. To reach the necessary depth each scribe was done in ten passes. The second batch was not laser scribed and served as a reference ensuring that the measurement errors, i.e. due to drift effects, are minimal. The electrical characterization took place before the laser scribing, after the laser scribing and after the mechanical breaking, see Fig. 1.

The current-voltage curves were determined with an automated cell measurement system that is capable of measuring both full-cells and half-cells. Thus, all cells have been measured on the same tool under identical measurement conditions. The measurements include a flash-measurement to determine the short circuit current and the open circuit voltage, a steady-state current-voltage characterization yielding the fill factor, a dark-I-V-curve giving the parallel resistance, and an I_{sc}-V_{oc}-measurement yielding the saturation currents. In order to obtain conclusive results, the measurements must be carried out with very high measurement precision.

3. Losses induced by the laser-based cell separation

The focus of the data analysis has been on the parallel resistance R_p and the recombination currents J_{02} as well as their influence on the total cell efficiency. In order to evaluate the typical impact of the R_p-change and the J_{02}-change on the cell efficiency a two-diode model has been considered using typical parameters obtained for a full cell. Then, the simulation has been repeated with either $R_{p,before} \rightarrow R_{p,after}$ or $J_{02,before} \rightarrow J_{02,\,after}$ changed. This yields an indication on how much the efficiency is affected by either of the two parameters.

3.1. Multi-crystalline cells vs. mono-crystalline cells

In Fig. 2 (left), the shunt resistance values of the two cell batches before and after the cell separation based on laser process LP1 is shown. The initial values for the shunt resistance of the mono-crystalline cells are higher than for the multi-crystalline cells, as expected. In either case, the cell separation process lowers the R_p values. Additionally, the variation among these values is increased. This is an indication that the cell separation process induces defects that are very inhomogeneously distributed. The spread is larger for the mono-crystalline cells. This can be explained by the fact that the mono-crystalline cells themselves are more homogeneous showing less shunt-like defects than the multi-crystalline cells. Quantitatively, the median value of the shunt resistance is changed from $R_{p,full} \cong 640k\Omega cm^2 \rightarrow R_{p,half} \cong 250k\Omega cm^2$ for the multi-crystalline silicon batch and from $R_{p,full} \cong 1M\Omega cm^2 \rightarrow R_{p,half} \cong 125k\Omega cm^2$ for the mono-crystalline batch. However, this reduction of the shunt resistance value does not lead to a significant reduction in the cell efficiency.

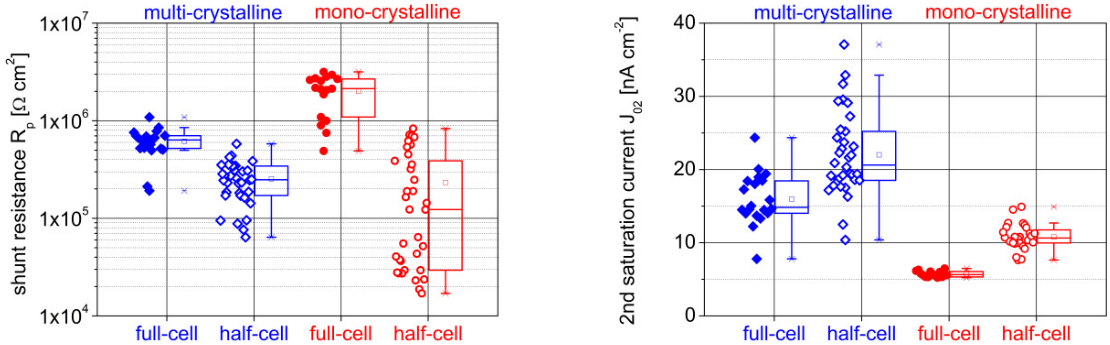

Fig. 2: Distribution of shunt resistance R_p (left) and recombination current J_{02} (right) before and after the cell separation. The blue symbols represent the batch of multi-crystalline silicon solar cells while the red symbols show the results for the mono-crystalline solar cells.

In a second step, the loss current as given by J_{02} is studied. This contribution gives an indication on the recombination processes. Initially, the loss current defined by J_{02} is significantly smaller for the mono-crystalline cells. For either cell type, the cell splitting increases this loss contribution. The median values of J_{02} are changing from $J_{02,full}$ = 15nAcm^{-2} → $J_{02,half}$ = 21nAcm^{-2} in case of the multi-crystalline cells and from $J_{02,full}$ = 6nAcm^{-2} → $J_{02,half}$ = 11nAcm^{-2} for the mono-crystalline cells. In contrast to the decreased R_p, these changes imply a relative reduction of the cell efficiency of about -0.7%$_{rel}$.

3.2. Stepwise separation-process analysis

The second experiment aims at an identification of the process step that induces the larger damage with respect to the electrical performance of the half-cells. In particular, it is studied whether the increase of J_{02} can be attributed to the laser scribing or to the subsequent mechanical breaking of the cells. To this end, further optimization studies on the cell separation process have first been performed. Based on this further optimized laser process LP2, a batch of eight cells has been investigated with respect to the median J_{02} values in comparison to a reference batch that was not laser-scribed and broken. These two batches were electrically characterized three times: initially before the laser scribing, after the laser-scribing, and finally as half-cells after mechanical breaking. The relative change in J_{02} is shown in Fig. 3. It can be observed that the major increase in the J_{02} parameter is associated with the laser scribing step.

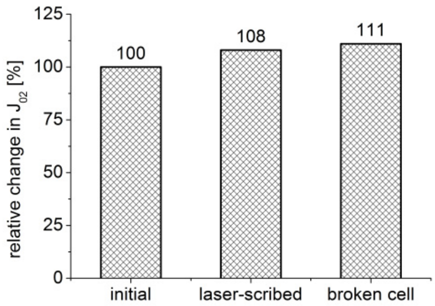

Fig. 3: Relative change of the loss current parameter J_{02} during the individual steps of the cell separation process in comparison to a reference batch.

4. Conclusions

The development of a new type of more efficient PV-modules based on half-cells requires an in-depth understanding of the losses that are induced by the laser separation process. Generally, a new cell edge might lead to lower parallel resistance of the cell (shunting) as well as to higher recombination at the new surface given by the additional edge. In this work, two different cells types have been split into half-cells by means of a laser-scribing and subsequent cell-breaking process. The cells were characterized by current-voltage measurements before and after the cell splitting. Finally, a statistical data analysis with special focus on the values of the parallel resistance and the loss currents due to recombination has been applied.

It is found that both the shunting and the recombination increase significantly due to the laser separation process. However, simulations based on the two-diode model show that only the increased recombination implies an efficiency reduction if the laser process has been sufficiently optimized. Furthermore, it is found that the laser-scribing leads to the major contribution regarding the J_{02} increase in comparison to the cell-breaking step. This implies, that the focus of the cell separation process should first of all lie on an optimization of the laser-scribing.

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