FIRST STEPS TOWARDS AN AUTOMATED REPAIRING OF SOLAR CELLS
BY LASER ENABLED SILICON POST-PROCESSING

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ABSTRACT: In industrial solar cell production of c-Si solar cells rejects in the range of several percent depending on the manufacturing line are inevitable. Making use of this resource could significantly increase the yield of production leading to lower manufacturing costs. Laser post-processing of defective cells has shown a high potential for repairing cells with local defects like shunts and was proposed for large scale testing. In this work first results are presented for an automated laser repairing and post-processing system that could be placed at the end of a manufacturing line. 450 rejected standard Cz-Si solar cells from a large cell manufacturer were characterized by means of optical inspection, IV- and luminescence measurements. The common cell defects are presented and the electro- and photoluminescence technique is discussed for being used as characterization method for an automated repairing system. Results of first manually laser repaired cells are shown and a preliminary technical draft of the automated system is exposed.

Keywords: Manufacturing and Processing, Laser Processing, Defects, Electroluminescence, Photoluminescence

1 INTRODUCTION

Despite of the tremendous cost reduction of PV modules in the last years it is still an overall goal of the PV industry to lower module manufacturing costs in order to become more competitive to other technologies for energy recovery. Therefore a lot of research is focused on developing more efficient photovoltaic concepts and processes or replacing or saving expensive materials. Another approach we follow in the REPTILE project is to reuse solar cells, that are rejected at the end of the production process, by laser post-processing. The goal of an automated system at the end of a manufacturing line could significantly increase the production yield leading to a direct benefit for the cell producer.

Abbott et al. used PL for detection of localized shunts in industrial mc-Si solar cells and clearly increased the cell performance by laser isolation [1]. Also an improved isolation technique using additional silver etching was shown [2] and two-diode-model analysis of IV results from laser isolated cells were issued [3]. Furthermore defective parts of solar cells were laser cut and patched with cell pieces [4]. ITS Innotech reuses rejected solar cells from different cell manufacturers and repairs them in external facilities [5].

In the REPTILE project we investigated 450 defective standard Cz-Si solar cells from a large cell manufacturer in order to define the typical present defects. For laser post-processing we focus on laser isolation of shunts and laser cutting of cells with large-area defects.

2 MEASUREMENTS

2.1 IV measurement

280 of the rejected solar cells were measured with a commercial available IV flasher (Berger) and 170 with a self-made steady-state sun simulator both at STC conditions. In Fig. 1 on the left side the efficiency distribution of the cells is shown. The maximum cell efficiency is 18.3%, 30% of the cells have a performance of 18% or higher and a clear smearing out towards lower efficiencies is visible.

One reason for the performance drops are low shunt resistances of the cells as pictured on the right side of Fig. 1. 63% of the cells have shunt values of 20 Ω or lower. 19% are strongly shunted with Rs lower than 1 Ω.

In Fig. 2 the distribution of the series resistance of the cells measured with the IV flasher is imaged. The Rs values of the sun simulator cannot be compared to the flasher values and are not pictured in the plot. The distribution reveals that 42% of the cells have an increased series resistance of 0.75 Ωcm² or higher.

Figure 1: Efficiency (left) and shunt resistance distribution (right) of 450 rejected Cz-Si solar cells from mass production. The interval of the efficiency plot is 0.2% and 1 Ω for the shunt resistance plot.

Figure 2: Distribution of the series resistance of 280 rejected cells in intervals of 0.05 Ωcm² (IV flasher data).
2.2 Optical inspection

All 450 solar cells were examined visually with the naked eye. This was done for two reasons. Firstly optical defects accord to defects visible by luminescence techniques in a higher degree than expected and thus are an interesting characterization method. Secondly optical systems are well established in cell production lines and could potentially feed an automated repairing system with space-resolved data.

Table I lists all relevant optical defects found on the samples. The most common defects are finger interruptions that do not have high impact on the cell performance. Cracks are present on 34% of all cells. Cells with cracks should not be used for module production so the reuse potential is limited to laser cutting into smaller solar cells. A very common defect are metallic spots on the front metallization that are partially also visible on the cell back. Luminescence measurements revealed that these defects most probably are strongly shunted breakthrough spots coming from reverse voltage tests in the cell production. Sometimes breakthrough spots appear as finger interruptions and cannot be distinguished from them with the naked eye. 10% of the cells have localized printing stains on the front side. If it is aluminum paste these spots also lead to strong shunts. Striking bright parts of the back aluminum are visible on 8% of the cells. These defects correlate to low contact resistance areas on the back. 7% of the cells show breakages and 7% of the cells have ARC color defects. Most of the ARC color defects are minor color inhomogeneities that do not influence the cell performance remarkably. However the cell ARC color is important for a homogeneous appearance of solar modules. Only 6% of the cells do not show any optical defects and 4% have stains not coming from paste.

Table I: Appearance of optical defects in rejected Cz-Si solar cells.

<table>
<thead>
<tr>
<th>Optical defect</th>
<th>% of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger interruption(s)</td>
<td>58</td>
</tr>
<tr>
<td>Crack</td>
<td>34</td>
</tr>
<tr>
<td>Metallic spot</td>
<td>28</td>
</tr>
<tr>
<td>Printing stain</td>
<td>10</td>
</tr>
<tr>
<td>Aluminum color</td>
<td>8</td>
</tr>
<tr>
<td>Breakage</td>
<td>7</td>
</tr>
<tr>
<td>ARC color</td>
<td>7</td>
</tr>
<tr>
<td>No defect</td>
<td>6</td>
</tr>
<tr>
<td>Stain (other)</td>
<td>4</td>
</tr>
<tr>
<td>Rare defects: Missing aluminum,</td>
<td>&lt;3</td>
</tr>
<tr>
<td>smeared / thin front printing,</td>
<td></td>
</tr>
<tr>
<td>holes, minor topographical</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Luminescence measurements

Luminescence techniques are known to be a versatile and fast tool for space-resolved solar cell and wafer characterization. Single EL pictures show a correlation to the local series resistance, PL images under open circuit conditions correlate to the minority carrier lifetime and picture shunts [6].

We used EL and PL to characterize all rejected cells. On the one hand luminescence measurements are able to detect most of the defects that lead to performance loss of solar cells and on the other hand we want to analyze the capability of EL and PL to be used as characterization tool for an automated repairing device requiring exact defect localization capability. We found four different groups of defects that lead to significant loss of performance:

The most common defects are shunts. From the IV measurement we know that 63% of the cells have $R_{sh}$ values lower than 20Ω (~5kΩcm²). 97% of the shunted cells were recognized by the luminescence measurements. As long as the shunt does not lie on the busbar the shunt position can be well detected represented as a dark spot with high contrast. It is known that on luminescence images the contrast of a shunt depends of the front metallization structure in the shunt’s vicinity [7]. If the shunt lies on the busbar the exact position often cannot be determined well or not at all depending on the shunt resistance. An example of a PL image of a strong shunt on the busbar is displayed.
in Fig. 4. 19% of all detected shunts are located underneath busbars. Most shunts are strongly localized, can be very well detected by EL or PL and show a high potential to be repaired by laser isolation as long as no crack comes along with it.

The second most common defects are cracks or breakages that occur at least on 41% of all cells. As we did not use special (micro-)crack detection equipment on the samples the real amount of (micro)cracks is not known. The value 41% comes from the optical inspection as the luminescence techniques only revealed only 31% of the cells being cracked or broken. On problem are short cracks around shunt spots that cannot be well detected by the luminescence techniques. Cracked or broken cells can just be reused by laser cutting. As most cracks and breakages do not influence the whole cell area cracked cells show a good potential for reusing.

The third and fourth groups of most common defects are back metallization problems with 22% of all cells and front metallization defects that only 5% of the cells show. Metallization defects can be perfectly detected by EL and occur as dark areas. In PL images these parts occur as bright spots (see Fig. 3). Interestingly half of the back metallization defects can be seen on the back with the naked eye as bright parts of the aluminum printing while all front metallization defects can be detected visually.

The relative high amount of 10% of the cells that have ARC color defects are mostly minor color inhomogeneities that do not influence the cell performance remarkably and thus are neglected in this work. However color inhomogeneities are an aesthetic problem for possible use in modules.

3 REPAIRED SOLAR CELLS

3.1 Laser isolated shunt

First tests of laser post-processing of defective solar cells were done and one example of a repaired cell by laser isolation of a shunt defect is shown in Fig. 5. The corresponding electrical properties of the cell before and after isolation are pictured in Table II. For isolation a single laser process step was executed.

The IV values show minor changes but the shunt resistance was increased from $6\Omega$ to $49\Omega$. This leads to an increase of the reverse bias performance of the cell. Because of the cell’s low breakdown voltage before repairing it was rejected. After laser repairing the reverse characteristics allow reuse in solar modules.

![Figure 5: a) EL image at 8A of a local shunt before laser isolation and b) after isolation of a rectangular area around the shunt spot. The rectangular area was determined a little too narrow as a small part of the shunt on the upper left corner is still visible.](image)

| Table II: IV results and reverse characteristics before and after the laser isolation of the cell from Fig. 5. |
|-----------------|-----------------|-----------------|
|                 | before          | after isolation |
| $\eta$ [%]      | 17.9            | 17.8            |
| $V_{OC}$ [mV]   | 626             | 628             |
| $j_{SC}$ [mA/cm²] | 36.9          | 36.8            |
| FF [%]          | 77.5            | 76.9            |
| $R_{Sh}$ [Ω]    | 6               | 49              |
| Reverse I [A]   | -0.4@-2.5V      | -0.3@-12V       |

It is also important to note that the IV measurements were performed under standard conditions. In this case medium shunts do not have dramatic influence on the cell efficiency. But on low light irradiation medium shunts lead to an increased efficiency drop. This is also a reason for sorting of shunted cells.

3.2 Laser Cutting

Laser isolation of defects is suitable for shunted cells but for other defects our repair strategy is laser cutting. In the two examples of Fig. 6 we just used a standard edge isolation laser (ns-fiber-laser, 1064 nm) with lower laser scan velocity on the sample to scribe grooves on the backside followed by manually snapping of the cell. In Fig. 6 a) a cell is shown with a long crack. The best way of reusing such a cell is cutting it into two parts as seen in b). Now the left part can be build in a half-cell-module and the right part is scrap. The original cell had an efficiency of 18.0% while both cut parts reach around 17.4%.

In Fig. 6 c) a cell with back contact problems and weak shunts on the right side is pictured ($\eta=17.0\%$, $R_{Sh}=18\Omega$). We cut these cells in stripes of around 2 cm width with equal cell areas. Such cells can be used in special application modules. The efficiencies of the 6 stripes on the left side are in the range of 16.6% to 17.2% with an outlier of 15.7%. Both stripes on the right side have

![Figure 6: EL images of laser cut solar cells. a) Long crack in cell. b) Halved cell from a), the left part of the cell can be reused in a half-cell-module. c) Cell with metallization and shunt defect. d) The cell of image c) cut into eight stripes with equal cell area. All EL pictures taken under 8A except of d) for which 1A was used.](image)
efficiencies of 13.2% and 12.7% with low shunt values. With this method a maximum of cell area can be reused. All cut cells show increased series resistance. This is probably due to a suboptimal contacting of these special size cells during IV measurement. Therefore the efficiency values given here should be considered as conservative values.

4 FIRST DRAFT OF AUTOMATED SYSTEM

The plan for the automated cell repairing system (‘Cell Doctor’) includes the use of only one or two characterization systems followed by a single laser step that just uses one laser source for both cutting and isolation. As it is designed to be fed by one modern cell production line the process time of one cell can be up to 10 seconds offering a wide time window for characterization, processing and handling. EL has shown good performance on shunt detection and perfect recognition of contact defects. Therefore it is the preferred method for the Cell Doctor. However PL would have the big advantage to work contactless but its metallization defect recognition is clearly weaker. In order to perfectly localize all shunts which are the most common defect it would be also possible to add a thermographic characterization element.

In Fig. 7 the first technical draft of the system is presented. On the upper right corner the device is fed with rejected cells either directly in-line or by a cell carrier. The grabber then transfers the cell on a rotating table. On this table several process elements can be placed, in Fig. 7 it is one characterization unit and one laser unit. The advantage of the rotating table is that the cell does not have to be positioned again between the process steps. After processing the cells get sorted into different bins.

Figure 7: First technical draft of the automated cell repairing system with the code name ‘Cell Doctor’. The rotating table in the middle enables exact alignment for all process steps.

5 SUMMARY

In this work we presented the results of measurements on 450 rejected Cz-Si solar cells from mass production. IV results revealed series and shunt resistance problems. EL and PL images allowed categorization of the cells into four major defects classes; shunts, cracks and breakages, back metallization defects and front metallization defects. One representative example of laser isolation was presented with a clear increase of the shunt value while showing the same performance at STC. Also two cells with large area defects were cut in half respectively in eight parts enabling reuse for solar modules. Finally a first draft for an automated laser repairing system was presented.

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7 REFERENCES