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Controlled introduction of cracks into crystalline silicon solar cells and subsequent acoustic excitation

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Abstract

Due to the high cost pressure in solar module manufacturing over the last years the need for investigation of module quality (reliability, lifetime, security) has become more important. To investigate the long time behavior of solar modules both in the field or in the lab it can be beneficial to simulate typical defects in components of solar modules. In this work two different methods are presented to introduce artificial mechanical defects into standard silicon solar cells. Furthermore the dynamic behavior of cracks is investigated during strong acoustic excitation using a self-made excitation setup and photoluminescence techniques.

In the first method a steel ball is dropped in a controlled way on a mounted solar cell leading to a reliable introduction of a cross-shaped crack. In the second method a pendulum is used to introduce mechanical edge defects in solar cells which always leads to chipping of silicon but not necessary to crack introduction. By investigation of over 100 samples it can be shown that mc-cells have a higher probability of breaking if initial mechanical defects are present at the edge compared to Cz-cells. Furthermore no evidence was found that the edge isolation method (chemical or laser) could influence the breaking of solar cells with damaged edges. Also it is shown that cracks close to the edge lead to a higher chance of breakage compared to cracks in the center of the solar cell.

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Keywords: Defect; Crack; Durability; Acoustic excitation; Sonic treatment; Photoluminescence

1. Introduction

For the last years the competition in the solar module market is strongly increasing with steadily dropping module prices. For solar module manufactures this high cost pressure leads to the need for a more efficient module production. But the high cost pressure holds the risk of lower module quality because of cost savings in quality assurance and material quality. For this reason testing of solar modules both in the field and in the lab has become

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more important over the last years. In this work we try to simulate typical defects of components of solar modules in order to later build test modules and use them in long-term tests. Here it is important to establish defect simulation methods that are reliable and reproducible. We present two techniques that aim to introduce cracks in standard silicon solar cells, in the first method a steel ball is dropped on the sample and in the second method a pendulum is used for edge defect introduction. In addition the damaged samples are acoustically excited in a way that the samples oscillate in resonance. In photovoltaics acoustic excitation to examine wafer defects is already known [1]. The sonic treatment allows us to gain general information about the dynamics of mechanical defects like cracks in solar cells. Further we use it to be able to better estimate whether cells with simulated defects can be handled in module production processes, e.g. unwanted module defects could occur or certain module processes could become impossible at all. This work is about cracks because cracks are a common defect in solar modules that can lead to more severe damage over time which affects the security and performance of the module. Known ways of common introduction of cracks are for instance transportation [2] or heavy loads like snow or wind [3]. To investigate the crack propagation we use photoluminescence (PL) techniques.

2. Experimental setup

The ball-drop setup is imaged in Fig. 1 (a), it is built similar as described in [4]. The cell sample is mounted on a brass chuck using vacuum suction. The steel ball has a diameter of 6.4 mm, a mass of 1 g and was taken from a ball bearing. The ball is hold by a magnetic coil, the height of the coil and the position relative to the cell sample can be adjusted. A drop height too low does not reliably introduce cracks while a drop height too high leads to multiple cracks as the ball bounces from the sample. It was found that a drop height of 70 mm is optimal to introduce cracks reliable and reproducible. In Cz-samples always cross-shaped cracks occur while in mc-samples the cracks are star-shaped with three or more arms. The crack diameter lies between 3…10 mm. In the experiment described later in this document a constant drop height of 70 mm was chosen. For both Cz- and mc-samples two different crack positions were investigated. The first position (center) lies in the center of the cell around 10 mm next to the busbar in the middle. The second position (edge) is also next to the middle busbar but 3…9 mm close to the cell edge.

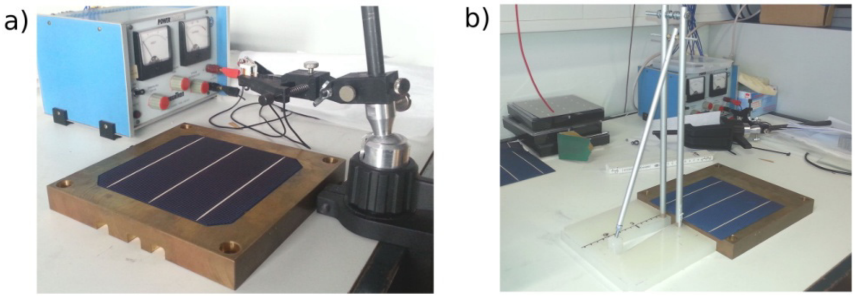

Fig. 1. (a) ball-drop setup; (b) pendulum setup.

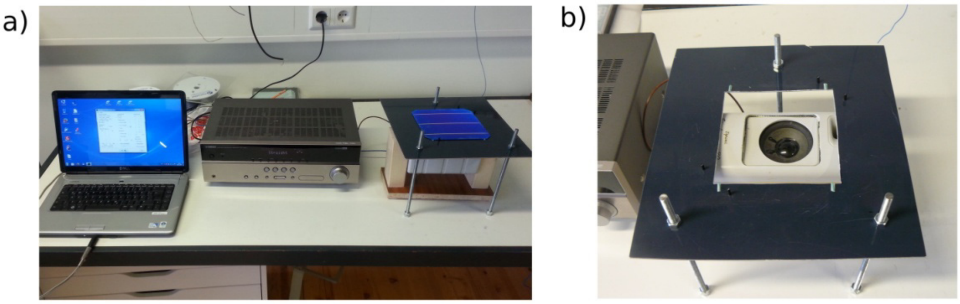

Fig. 2. (a) complete acoustic excitation setup with laptop, HiFi-amplifier, loudspeaker and sample holder; (b) sample holder in detail.

The pendulum setup is pictured in Fig. 1 (b). It is made of a 30 cm long aluminum rod with a diameter of 8 mm. At the end of the rod, at the point where the pendulum hits the cell edge a steel nut is mounted. This prevents the rod from taking damage from the samples and offers a more pointed hit area. The deflection of the pendulum can be controlled using props of different heights. In the experiment described later we worked with two different deflections 10 cm and 18 cm, the latter one leading to a 3.6 times higher pendulum energy. During the hit process the cell must be fixed manually. The pendulum hit always breaks silicon chips from the sample edge. As defect position we also chose ~10 mm next to the starting point of the busbar in the middle.

The acoustic excitation setup is designed to excite solar cells with sonic waves such that the sample vibrates strongly. To reach this the frequency of the sonic waves must be the same as the normal frequency of the sample in order to reach resonance. The resonance frequency for both Cz- and mc-cells was found to be 200 Hz. The setup is pictured in Fig. 2. For frequency generation the sound chip of a laptop and simple synthesizer software was used. A commercially available loudspeaker ("Computer speaker") with a diameter of approx. 55 mm was used for sound generation. Signal amplification was done with a standard HiFi-amplifier. The sample-holder is placed over the loudspeaker. It consists of a tripod and a metal plate with a squared hole in it. The sample rests on four narrow rubber supporting points. As the sample is moving during excitation four stopper pins prevent it from moving out of the excitation area. The loudspeaker is placed below the center of the sample, the distance from speaker to sample is 15 mm.

The investigation of cracks in the cell samples is done using photoluminescence (PL). At ISC we use a self-made PL-setup that excites the samples with laser-light of 808 nm and an intensity of around two sun equivalents. A deep-depletion, back-illuminated Si-CCD is used combined with a gallium arsenide wafer as long-pass filter in front of the camera objective. On mc-samples PL-quotient-images were made. This technique allows the recognition of smallest differences between two PL-measurements. In this work we use it to check for crack propagation. One image is taken from a sample with crack before exposure to sonic waves and one image afterwards. By dividing every pixel-value of the first image from the second the result is an image only showing differences. If a crack grows the new crack part appears very bright on the quotient image.

In this work we consider a crack as a narrow dark line on a PL-image. The crack length we define here as the direct distance between the starting and endpoint of the longest crack line in a cracked solar cell. As breakage of a solar cell during the acoustic treatment we define here either the breaking off of considerable parts of the cell or the formation of a crack so long that the resonance frequency of the sample changes whereby the excitation stops. In the latter case the sample always breaks apart by slightest handling.

As test samples we use standard industrial, p-type solar cells with Al-BSF made from mc- and Cz-silicon. All have the size of 156 x 156 mm^2 and exhibit three busbars.

3. Results and discussion

3.1. Acoustic excitation of undamaged solar cells

In a first experiment we chose twelve undamaged solar cells (six Cz- and six mc-samples) and exposed them to sonic excitation in order to investigate whether the sonic treatment itself might introduce defects. The controlling of the integrity of the cells was done via visual inspection, electroluminescence (EL) and PL measurements. Three different excitation intensities were selected, Table 1 lists the sample size for each intensity and gives the electrical parameters of the loudspeaker for all three intensities. Direct acoustic measurements of the sound pressure could not be done. The excitation was done in intervals up to an excitation time of 600 s in total. Between every interval a PL measurement was done.

Table 1. List of excitation intensities, sample size and electr. parameters of speaker.

Volume	Cz-samples #	mc-samples #	Voltage [V]	Current [A]	Power [W]
low	2	2	0.81	0.10	0.08
medium	2	2	1.92	0.24	0.47
high	2	2	4.53	0.60	2.74

None of the samples showed any mechanical defect through the sonic treatment. This was checked using visual inspection, PL and PL-quotient images. In all further experiments the strongest acoustic intensity was used for excitation (high volume).

3.2. Crack introduction through ball-drop

In this experiment we selected 40 undamaged solar cells and introduced a single crack in every sample using the ball-drop setup. In total there are four sample groups (see Table 2), on half of the samples the crack was introduced close to the center and on the other half close to the edge. Before and after the crack introduction a PL image was taken. Then the samples were excited in steps of 10 s, 30 s, 90 s and 240 s in total. After every step another PL image was taken. In Fig. 3 an example of a mc-cell with crack in the center is pictured before treatment (a) and after sonic excitation (b). Also an example of a Cz-cell with a crack at the edge can be seen before treatment (c), after 10 s of excitation (d) and after 30 s of excitation (e).

It was surprising to see that only two out of ten samples with a crack in the center broke during the testing. However four (Cz) respectively six (mc) out of ten samples broke if the initial crack was placed close to the cell edge. It seems like cracks close to the edge lead to a higher breaking rate. A clear difference between the behavior of Cz- and mc-samples cannot be seen, therefore a greater sample size would have to be investigated.

Table 2. List of sample groups for ball-drop experiment and amount of cells broken during acoustic treatment.

Group	Cell type	Crack location	Sample size #	Samples broken #
Cz-center	Cz	Center	10	2
Cz-edge	Cz	Edge	10	4
mc-center	mc	Center	10	2
mc-edge	mc	Edge	10	6

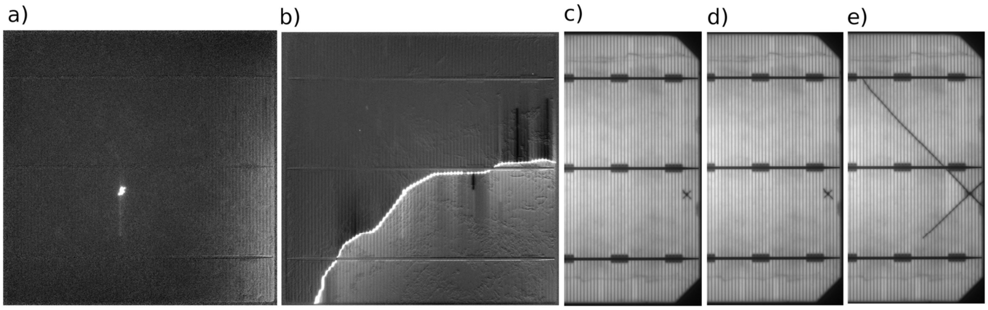

Fig. 3. Two examples from the ball-drop experiment before and after sonic treatment; (a) PL-quotient-image of mc-cell with inital crack in cell center; (b) PL-quotient-image of cell from (b) after sonic treatment; (c) PL-image of Cz-cell with initial crack close to cell edge; (d) PL-image of cell from (c) after 10 s of sonic treatment; (e) breakage of Cz-cell from (c) after 30 s treatment.

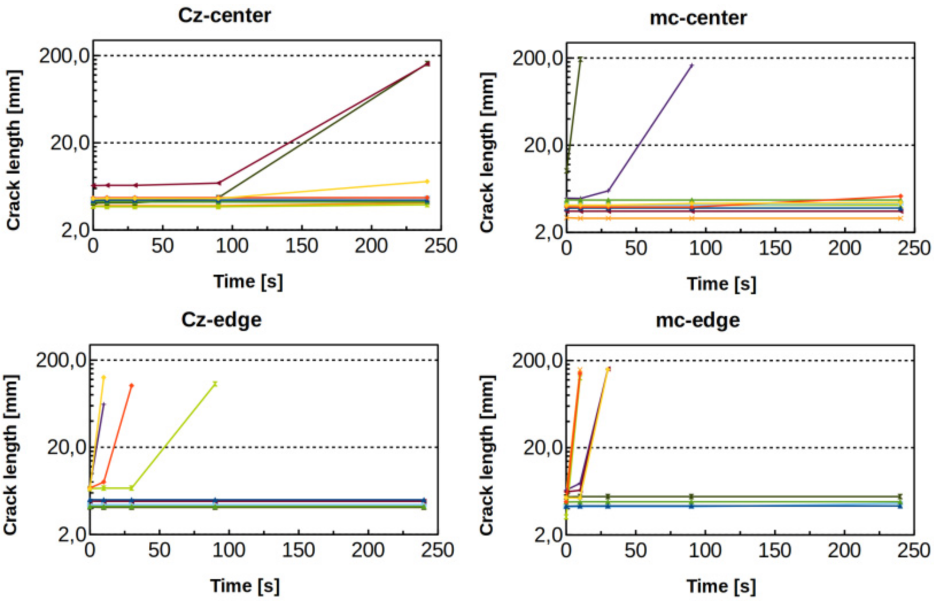

Fig. 4. Crack length depending on acoustic treatment time for all samples in the ball-drop experiment. Cells breaking can be easily spotted.

In Fig. 4 we see the dynamic behavior of the crack propagation in all samples. For every group the crack length is plotted over the excitation time. Breakage can easily be spotted by the strong increase of the crack length. Breakage as a result of cracks close to the edge does not only occur more often it also seems to happen faster. In general it looks like there are cracks that only grow little or not at all and there are cracks that lead to breakage. On the first glance it seems like breakage happens abrupt but with a closer look several samples can be found for which the crack propagation happens in two steps until breakage. The breakage probability might depend on the length of the initial crack. From all 40 samples all cracks longer than 5.5 mm (9 samples) lead to breakage while from cells with cracks equal or smaller than 5.5 mm (31 samples) only 5 samples broke (~16%) while 26 did not break (~84%).

3.3. Edge damage introduced by pendulum

In the pendulum experiment we used 64 samples divided in eight groups with eight samples each. Again Cz- and mc-cells were investigated with two different edge isolation types (chemical and laser) using two different pendulum deflections. Table 3 summarizes all groups. The pendulum hit always leads to typical chipping of silicon material at the cell edge both on the front and on the back. On the PL image the chipped material is always visible as a small, dark spot however not in every case a crack line is visible. The information whether an initial crack line is visible or not and the breakage rate of the sample groups is also displayed in Table 3. Example images of edge damage introduced by the pendulum can be found in Fig. 5. As in the previous experiment after damaging the samples have been excited acoustically in intervals of 10 s, 30 s, 90 s and 240 s in total with PL measurements in between.

As a first result it surprises that the breakage rate does not significantly differ for both deflection values. The amount of samples showing initial crack lines on the PL image is even higher in the group with the shorter deflection. A reasonable explanation for these results is yet missing. 20 samples show an initial crack line on the PL-image from which 13 break during the acoustic treatment (65%). 44 samples do not show initial crack lines and only 4 of those broke (~9%). These results suggest that despite of the chipping of silicon cracks are not necessary introduced by the pendulum hit. Therefore the pendulum method cannot be considered a reliable way to introduce cracks in solar cells. However it is reliable in introduction of edge damages with chipping of silicon.

Table 3. List of sample groups for pendulum experiment, amount of initial cracks visible on PL-image and amount of cells broken during acoustic treatment.

Group	Deflection [cm]	Cell type	Isolation type	Sample size #	Initial crack on PL #	Samples broken #
1	10	Cz	CEI	8	3	0
2	10	Cz	LEI	8	3	2
3	10	mc	CEI	8	4	4
4	10	mc	LEI	8	3	3
5	18	Cz	CEI	8	0	0
6	18	Cz	LEI	8	1	1
7	18	mc	CEI	8	3	4
8	18	mc	LEI	8	3	3

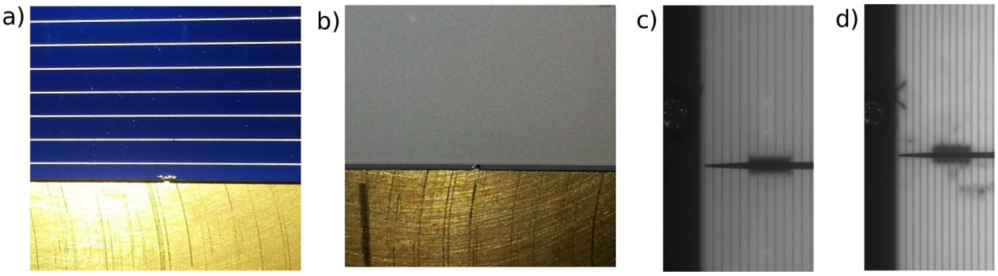

Fig. 5. Examples of defects introduced by the pendulum setup; (a) image of typical pendulum defect on sample front and (b) on back; (c) PL image of the corresponding cell, a crack line is not visible; (d) further example of a pendulum defect that leads to visible cracks on the PL image.

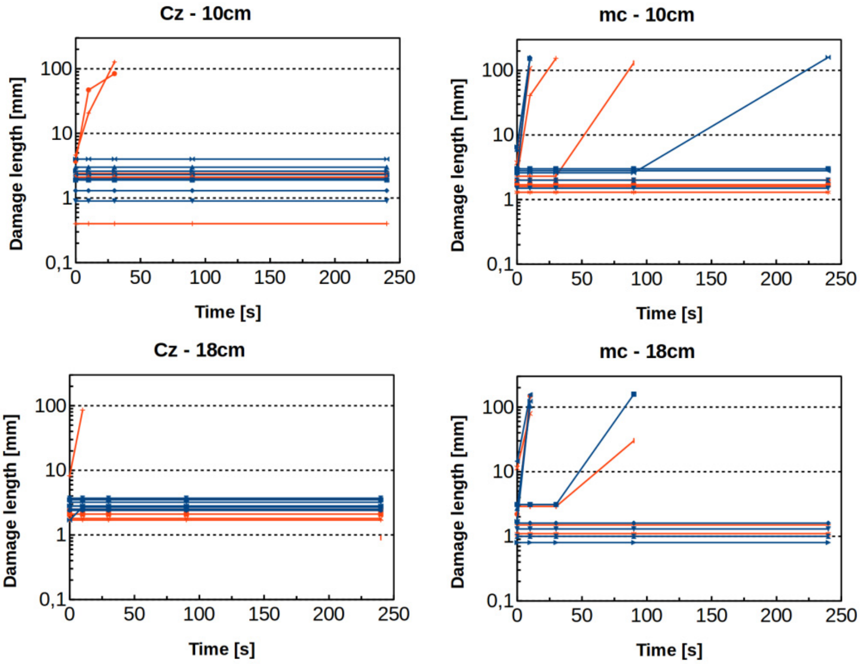

Fig. 6. Crack length depending on the acoustic treatment time for all samples from the pendulum experiment; the blue lines represent the samples with chemical edge isolation and the red ones samples with laser edge isolation.

If we compare the Cz- and mc-cells for a higher pendulum deflection Cz-cells show less initial crack lines. And regarding the breakage rate clearly more mc-cells broke during excitation (17 samples) compared to Cz-cells (3 samples). In Fig. 6 also the damage propagation over time is plotted like in the experiment before with the difference that the damage length is plotted and not the crack length. This means if a crack is visible the damage length is the crack length and if no crack is visible the damage length is the diameter of the dark spot of the defect on the PL-image. Red represents the samples with laser edge isolation and blue the ones with chemical isolation. No significant differences can be observed between these two groups. The sample size was too small for reasonable conclusions.

4. Conclusion

In this work we presented two methods to introduce mechanical defects into silicon solar cells. To investigate the defect propagation a setup for acoustic excitation of solar cells was introduced and used on more than 100 samples. PL was the primary measurement technique to analyze the defects. As samples standard industrial Si-cells with Al-BSF and three busbars were used, some with chemical and some with laser edge isolation. At first it was shown that the acoustic excitation does not introduce defects in undamaged solar cells. Then the ball-drop setup was used to introduce cracks in 40 samples and subsequent sonic treatment was applied. It could be shown that cracks in the cell center lead to lower breakage rates during excitation than cracks close to the edge. It also seems that samples with cracks next to the edge break faster. No significant difference between Cz- and mc-samples was observed and there is evidence that the breakage rate might depend on the initial crack length. At last the pendulum was used on 64 samples and the same acoustic treatment as before was applied. Only on ~31% of the cells the pendulum hit resulted in visible crack lines on the PL images making this method not reliable for crack introduction. Surprisingly the pendulum deflection did not increase the crack or breakage rate of the samples. Further clearly more mc-cells broke as result of the pendulum hit and the sonic excitation than Cz-cells and no significant difference between cells with chemical edge isolation and laser isolation was observed.

Acknowledgements

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