EDGE SHUNT PASSIVATION IN SILICON SOLAR CELLS BY CHEMICAL ETCHING INVESTIGATED BY LOCK-IN THERMOGRAPHY AND CELLO

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ABSTRACT

Shunts in solar cells are often localized at the edges. Some of these edge shunts have a linear (ohmic) behavior and some of them have a non-linear (diode-like) one. At least the linear edge shunts, which are the most dangerous ones, can be removed by local etching. Two proven non-destructive techniques for shunt imaging are lock-in thermography and CELLO. Lock-in thermography detects local heat sources under forward or reverse bias in the dark, whereas CELLO measures the small signal electrical response to a pulsed Laser beam at different voltages. These two techniques are compared with respect to their ability to investigate the influence of edge etching procedures on the shunt activity.

1. INTRODUCTION

It is well known that a lot of commercially produced silicon solar cells have a problem caused by local short circuits called shunts [1, 2]. These shunts may lead to a deterioration of the efficiency of solar cells by increasing the leakage current and decreasing both the open circuit voltage and the fill factor of the solar cells. Lock-in thermography [3] and CELLO (solar CELl LOcal characterization) [4, 5] are two non-destructive imaging techniques, both allowing to image shunts based on different physical effects. While lock-in thermography images the heat dissipated by the current flow across a shunt in the dark, CELLO detects the bias-dependent reduction of the LBIC signal caused by the parallel conductivity of a shunt. While lock-in thermography provides only information about shunts, CELLO also allows a mapping of the local series resistance. Both lock-in thermography and CELLO have proven that most of the critical shunts are localized at the edge area of solar cells (edge shunts) [3, 4]. The ohmic edge shunts are process-induced shunts, since they are produced by remainings of the emitter, which have survived the emitter opening procedure. It has been found that there are different types of edge shunts, some having a linear (ohmic) and some having a non-linear (diode-like) I-V characteristic [6]. The ohmic shunts are the most dangerous type of shunts due to the possibility to degrade the efficiency of solar cells more drastically than the diode-like shunts (especially under low level of illumination) and due to the possibility to become very active hot spots under reverse bias, which may cause a severe problem in modules. The bad influence at least of ohmic edge shunts on the solar cell efficiency can be avoided by an especially designed local chemical etching method (passivation) of the edges using KOH or other etch solutions or pastes [7, 8, 9, 10]. The principle of the passivation method is very simple: First a defined quantity of cold KOH solution (at room temperature) is deposited on the edge area. Then the wetted edge is heated locally e.g. by contacting a heating plate. In our contribution this chemical edge passivation procedure will be monitored both by lock-in thermography and by CELLO in order to investigate the ability of these different techniques to detect and prove the removal of various types of edge shunts.

2. METHOD

2.1 Edge-Shunt Passivation (etching)

As has been published earlier [7, 8, 9], a defined quantity of cold solution of KOH (10 - 30 %) is deposited at room temperature on the edge area of the solar cell by using a sponge saturated with KOH (see Fig. 1a). Then the wetted edge is heated up locally by using e.g. a heating plate kept at 100 - 140 °C (see Fig. 1b). In our experiment the other edges have been passivated sequentially, but, with slightly more sophisticated handling equipment, all edges can be passivated in parallel. Optionally a cleaning step with distilled water was applied.

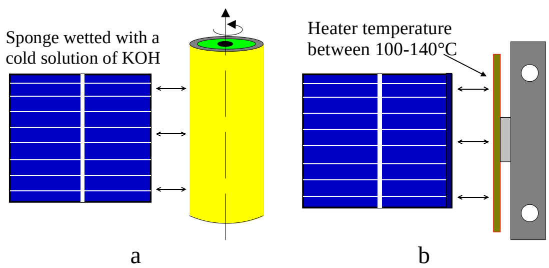

Fig. 1 A defined quantity of KOH is deposited at the edge of a solar cell (a), then the wetted area is heated up locally.

2.2 Characterization

The commercial lock-in thermography system TDL 384 M 'Lock-in' [11] and CELLO [4, 5] have been used to localize the shunt positions before and after the etching of the edges. The lock-in thermography maps have been measured at +0.5 Volt (forward bias) and at -0.5 V (reverse bias). The measurements at +0.5 Volt were made to find the shunts, which are active at the operating point of the solar cells. To check the linearity of the I-V characteristic of the shunts, the measurements at –0.5 Volt have been made. These results are always displayed in the same scaling as the results for 0.5 V forward bias. Only if the signal heights at +0.5 V and -0.5 V are the same, a shunt has a linear (ohmic) I-V characteristic. The CELLO maps of the linear current responses (dI_1, dI_2, and dI_3) have been measured potentiostatically at V_1 = –300 mV, V_2 = 0 mV, and V_m respectively, where V_m is the voltage of the solar cell at the maximum power (operating point) determined by the I-V characteristic of the illuminated solar cell. The relative currents in forward and reversed direction have been calculated by applying the equations (1) and (2), respectively. The relative current loss under reversed bias ΔI_{sh} compared to the short circuit condition indicates ohmic shunts. Strongly reduced relative currents in forward direction ΔI_{ser} are indications of strong ohmic losses due to a large local serial resistance or a bad local pn-junction [4, 5]. Thus, as an abbreviation the maps will be called shunt maps and serial resistance maps:

$$\Delta I_{sh} = 1000 * \left(\frac{dI_1}{dI_2} - 1 \right) \quad (1)$$

$$\Delta I_{ser} = 1000 * \left(\frac{dI_3}{dI_2} \right) \quad (2)$$

The CELLO maps before and after the passivation are displayed in the same scaling. Additionally, the success of the etching procedure will be monitored by measuring I-V curves for the solar cells before and after the local etching of the edge area. In order to investigate the kind of shunts and the possible improvement of the solar cell parameter after the passivation, the I-V curves in the dark at different temperatures (25, 35, and 45 °C) have been measured.

3. RESULTS

Parts of solar cells (6.25 x 6.25 cm^2) have been obtained by cutting (sawing) of a big 12.5 x 12.5 cm^2 commercial mc-silicon solar cell, which had an incompletely opened emitter at the edge area (poor plasma etching). Hence, each sample has two edges with a high density of ohmic edge shunts. Representative results of one cell are presented, the results of the other cells are similar. The electrical parameters of two investigated solar cells are summarized in Tab. I and II.

The lock-in thermography maps of one solar cell (see Fig. 2) under the both forward (a) and reverse (b) bias show, as expected, that the incompletely opened edges include strong ohmic shunts as well as diode-like shunts. Note that bright contrast in the lock-in thermography maps points to shunts. This measurement also reveals some weak linear and non-linear volume shunts, which were invisible in the original scaling. The CELLO map of shunts (see Fig. 2c, see arrows) shows a good correlation especially with the lock-in thermography map under reverse bias (see Fig. 2b, see arrows), whereby the dark contrast in the CELLO map represents ohmic shunts. The effective series resistance map of CELLO shows that the sample, in addition to the edge shunts, has another important fault, which are regions of high series resistance (see Fig. 2d). Here the black areas in the map are indicating regions of high local series resistance. This series resistance problem can also be observed in the I-V curves of the solar cell under illumination, both before and after the passivation (see Fig. 3).

Table I. The main solar cell parameters of the first sample before and after the passivation.

	$V_{oc}(V)$	$I_{sc}(A)$	$I_a(A)$	$V_a(V)$	$P_m(W)$	*FF*
before	0.577	0.504	0.406	0.451	0.1831	0.629
after	0.577	0.509	0.426	0.431	0.1836	0.625

Table II. The main solar cell parameters of the second sample before and after the passivation.

	$V_{oc}(V)$	$I_{sc}(A)$	$I_a(A)$	$V_a(V)$	$P_m(W)$	*FF*
before	0.577	0.497	0.407	0.451	0.1835	0.64
after	0.580	0.504	0.436	0.423	0.1844	0.63

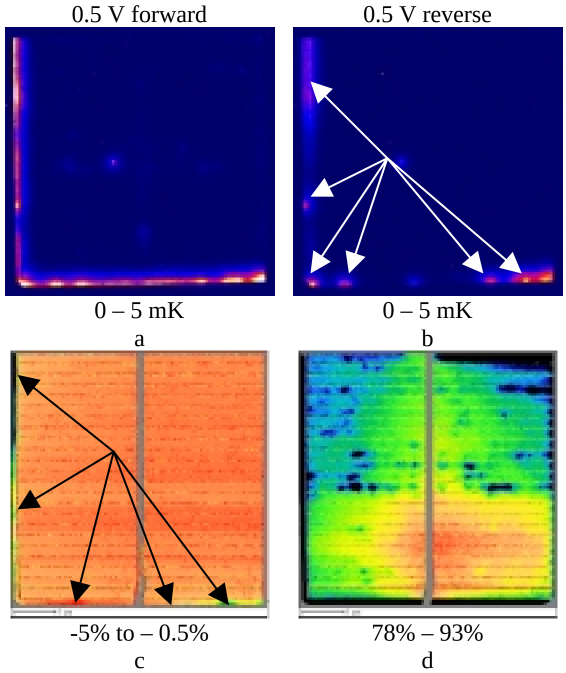

Fig. 2 Lock-in thermograms of a mc-Silicon solar cell under forward (a) and reverse (b) bias and the calculated CELLO maps of shunts (c) and of the effective series resistance (d) before passivation of two edges.

After the edge passivation the lock-in thermograms in Figs. 4a and 4b show that almost all the strong ohmic edge shunts have been removed (there are much less bright areas than before the passivation, especially under reverse bias) except one shunt, which is marked in Fig. 4b. Hence, the number of ohmic edge shunts has been drastically reduced after the etching of the edge area. The CELLO map of shunts shows that practically all shunts have been removed after the passivation (see Fig. 4c). The series resistance map of CELLO indicates that the local series resistance in the etched areas has slightly been increased (the black area has been increased).

In Fig. 5 the lock-in thermogram before edge passivation, displayed with increased contrast compared to Fig. 2a, is correlated again with the corresponding CELLO series resistance map. Interestingly, a correlation between some local weak heat sources and some positions of large series resistance is visible (see arrows). The detailed image Fig. 5c shows that the local shunt (X) in the area is lying below a grid line.

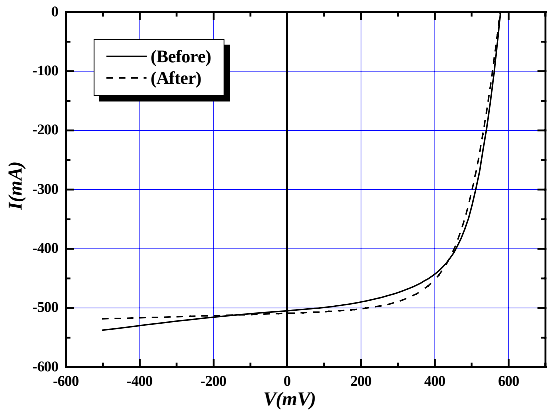

Fig. 3 The I-V characteristic of the solar cell under illumination before and after the edge passivation.

Another interesting result has been found, which is a small increase of the short circuit current for the two solar cells (see Table I and II). Actually we would expect a slight decrease of the short circuit current, since the cell area is decreased slightly by the etching procedure. The measured increase is due to a reduction of the current losses caused by the ohmic shunts in the edge region. Before edge passivation the photo current generated in the edge region was divided into one part flowing across the shunts and another part flowing to the emitter contact yielding the short circuit current. After edge passivation the whole photocurrent generated in the edge region is collected by the emitter contact.

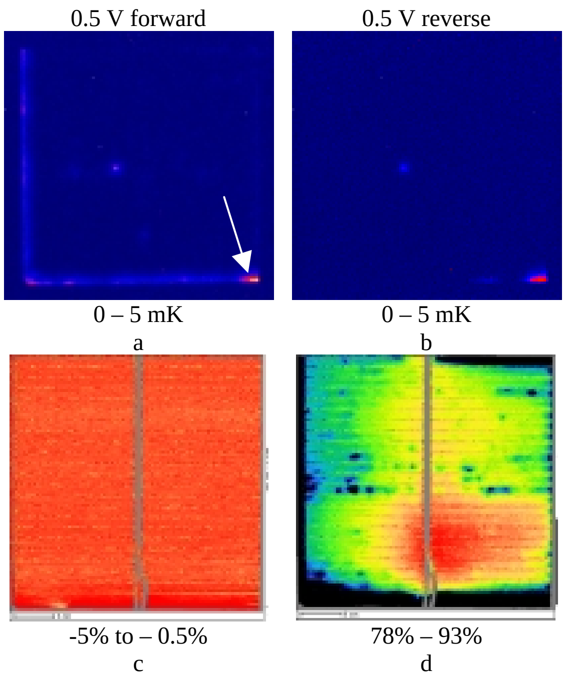

Fig. 4 Lock-in thermography maps of the mc-Silicon solar cell after the passivation of two edges in forward (a) and reverse (b) bias and the calculated CELLO maps of shunts (c) and the series resistance (d).

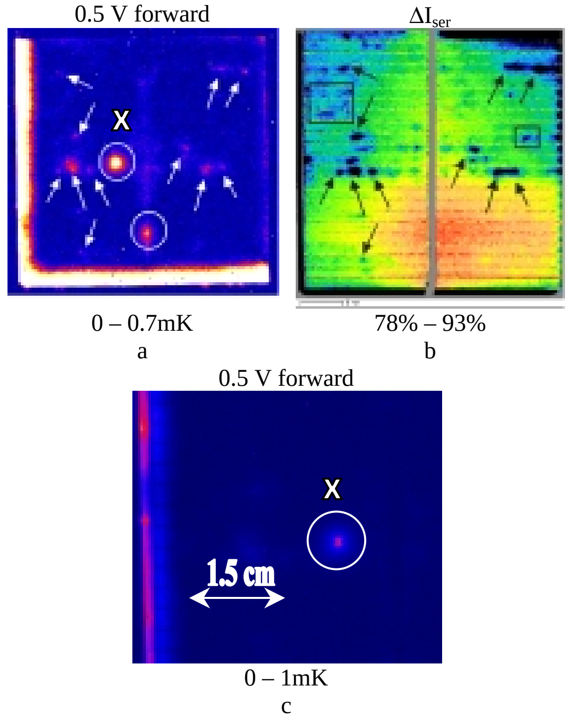

Fig. 5 The lock-in thermography map of the cell under forward bias displayed with increased contrast (a) shows a correlation with the effective series resistance map of CELLO in a lot of positions (see arrows in b). (c) is a detailed thermogram of the marked shunt "X" in (a).

4. DISCUSSION

As Fig. 4 shows, both non-destructive characterization techniques, lock-in thermography as well as CELLO, have shown that the majority of the ohmic edge shunts have been removed after the local etching of the edge area of the solar cell. Moreover, lock-in thermography shows that also the intensity of the non-linear shunts has been reduced. The CELLO map of shunts (Fig. 4c) clearly proves the success of the ohmic shunt passivation, since the dark areas in Fig. 2c have been removed after the passivation, and the shunt map has become very homogeneously. This shows that CELLO provides the possibility to show only ohmic shunts in this map and not the non-linear shunts, which are diminished but are still existing (see Fig. 4a). The successful passivation can also be proved by comparing the I-V characteristics of the solar cell in the dark, since the leakage current has been reduced very drastically from 727 mA to 131 mA at –2 Volt reverse bias (at room temperature, see Fig. 6). Further on, the dependence of the leakage current on the temperature has been inverted after the passivation from the ohmic type (decreasing of the leakage current by increasing of the temperature) to a diode-like type (increasing of the leakage current by increasing of the temperature).

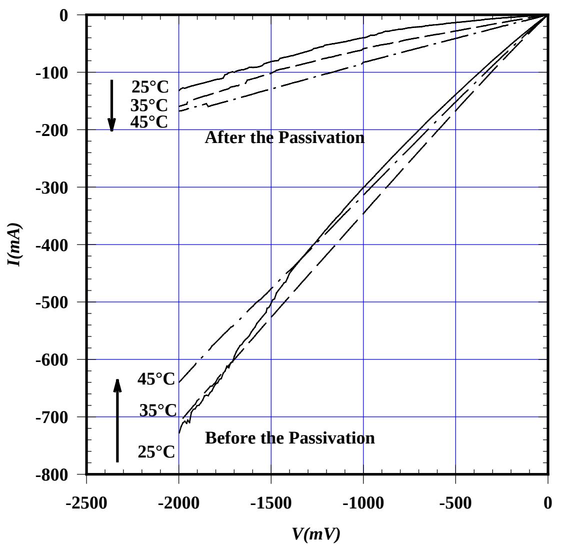

Fig. 6 The behavior of the leakage current in dependence on the temperature before and after the passivation.

Most solar cell parameters have been improved after the passivation, and the form of the I-V curve has become more ideal due to the decrease of the shunt resistance in the solar cell (see Figs. 3 and 6 and Tables I and II). There were no significant improvements of the fill factor in both solar cells (for the second sample a very small decrease of the fill factor has been measured) but the maximum power of the both samples has been improved after the passivation. In order to clarify this point it is very important to know that the main fault in the investigated samples is the inhomogeneous distribution of series resistance, since the I-V characteristic of the sample shows a bad slope in the region governed by the series resistance. This kind of defects cannot be passivated using our etching procedure. Note that CELLO is an optically based method being unable to see any shunts below grid lines as, e.g., the two marked shunts in Fig. 5a.

The unexpected correlation between regions of low series resistance detected by CELLO (Fig. 5b) and weak heat sources in the lock-in thermogram (Fig. 5a) is probably due to a local increase of the diffusion current in these regions. If the emitter doping concentration is lower in these regions, this leads to a higher series resistance as well as to a reduced barrier height. This barrier height reduction for the given forward bias of 0.5 V leads to an increased saturation current J_0 in these regions.

5. CONCLUSION

Two non-destructive techniques have been used to investigate the influence of our edge passivation procedure on the shunts at the edges of solar cells. Both linear and non-linear shunts in the investigated solar cells have been localized by using lock-in thermography. Most of the linear shunts have also been detected using the CELLO technique (if they are not localized under grid lines). However, non-linear shunts appearing only under forward bias are not visible in the CELLO shunt map. The used passivation method is very effective for removing the linear (ohmic) shunts (shown by lock-in thermography and CELLO) as well as for reducing the non-linear edge shunts (shown only by lock-in thermography). In contrast to lock-in thermography, CELLO provides the important information about the local distribution of the series resistance. Iit has been shown that removing edge shunts leads to a slight increase of the short circuit current.

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