LOCAL MAPPING OF THE OXYGEN-BORON COMPLEX IN 2x2 cm^2 AND 10x10 cm^2 HIGH-EFFICIENCY CZ-SI SOLAR CELLS BY LOCK-IN THERMOGRAPHY AND LBIC

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ABSTRACT

If high efficiency solar cells made from Czochralski material are exposed to sunlight or forward bias, their preformance degrades due to a rearrangement of complex which most probably contains oxygen and boron. This degradation, which can be reversed by annealing, is reflected not only in the solar cell parameters but also in the dark I-V characteristics. We have imaged the dark forward current across a 4 cm^2 cell and a 100 cm^2 cell containing striations by lock-in thermography after annealing the cell at 200°C and after degrading it for 24 hrs. The difference between these two images corresponds to the local action of the B-O complex. We have found that this complex is distributed homogeneously across both cells, and that some observed weak local shunts do not show any recombination-induced degradation. Especially, the striation pattern in the 100 cm^2 cell did not react on degradation and annealing.

INTRODUCTION

It is well known that solar cells fabricated from Czochralski (CZ) silicon material show a considerable degradation of their parameters if they are exposed to light [1, 2, 3]. A complex consisting of boron and oxygen atoms (B-O complex) is believed to be responsible for this degradation. This complex may exist in two configurations. Only one of them, which is formed during light exposure of the cell, is active as a recombination center. By annealing the sample at about 200°C this configuration can be converted into the other configuration, which is not recombination active. By light exposure or current injection the recombining configuration may be reactivated, a process which can be repeated many times. The degradation of the cell parameters measured under illumination is also reflected for the dark I-V characteristics: During degradation the dark current increases [2].

Lock-in thermography is a proven technique to image weak heat sources in electronic components and may be used e.g. to image shunts in solar cells [4, 5]. In this technique a pulsed bias is applied to a solar cell in the dark, and the temperature modulation at the surface is imaged with a highly sensitive infrared thermocamera. The data are evaluated by numeric lock-in processing and averaged over a certain acquisition time.

The advantage of lock-in thermography over stationary thermography is a dramatically improved detection sensitivity (from 20 mK to < 100 µK) and a considerably improved spatial resolution, since the lateral heat spreading is largely suppressed in this AC technique. Thus this technique is able to observe local changes of the dark I-V characteristic of a solar cell, which may be caused by B-O complex-induced degradation. These local changes should be proportional to the local B-O complex concentration, which can be mapped in this way.

INVESTIGATION OF THE PERL CELL

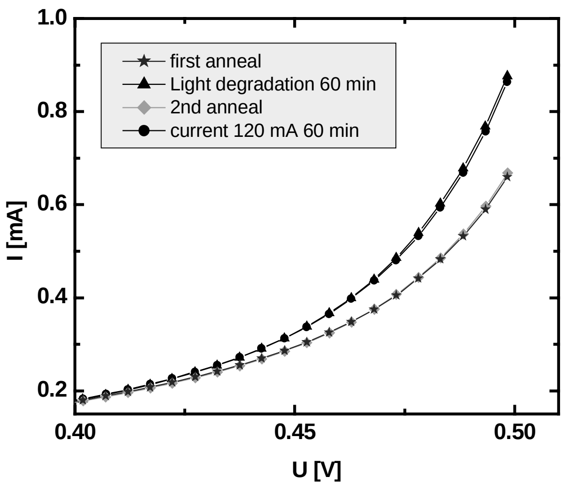

Fig. 1: Dark I-V characteristics of a CZ PERL solar cell after the first anneal, after 60 min. light degradation, after 2nd anneal, and after 60 min. current degradation

Our first investigations were made on a 4 cm^2 sized PERL solar cell manufactured at UNSW from CZ silicon material [6]. Both for the I-V characteristic measurements and for the lock-in thermography measurements the sample was thermostatted to 25 °C in order to obtain reproducable results. During the whole investigations (except of the light degradation) the sample was kept in the dark. First we have checked that the application of a forward current is equivalent to light irradiation to cause the degradation of the I-V characteristic. This is demonstrated in Fig. 1, where 4 dark I-V characteristics of this cell are shown: One measured after a first anneal for 30 min. at 200 °C, one after 1 sun light degradation for 60 min., one after a second anneal, which reestablishes the virgin state, and one after degradation by 120 mA current flow for 60 min. This current flow of 30 mA/cm^2 is roughly equivalent to 1 sun irradiation. Indeed, the I-V characteristic after current degradation coincides with that after the optical degradation. Hence, the degradation may be performed as well by forward current flow, which is easier to realize than light degradation. All degradations reported in the following have been performed current-induced rather than light-induced.

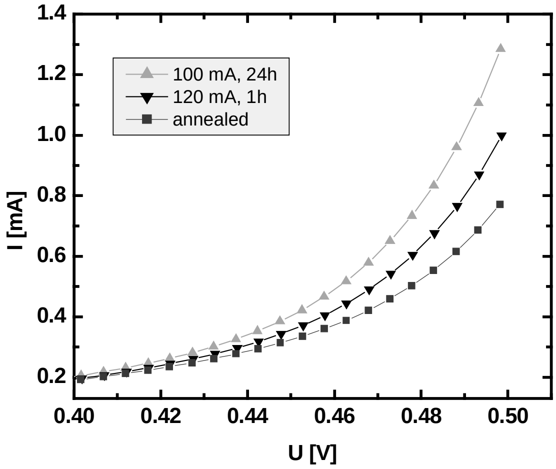

Fig. 2: The dynamic of current degradation

As a second step we have checked the dynamics of the current-induced degradation. Fig. 2 shows that after 1 hr the degradation is not complete yet. After 24 hrs the maximum current flowed and the I-V characteristics did not degrade anymore. Therefore, the following current degradation was performed for 24 hrs.

For imaging the B-O complex distribution over a solar cell, this cell was first annealed at 200°C for 1/2 hr and then kept in the dark in order to prevent light-induced degradation. Then a lock-in thermogram was measured at 0.51 V forward bias, corresponding to an initial dark current of 1.25 mA, which took about 1 hr. This low bias was selected in order to keep the unintended current-induced degradation during the lock-in thermography measurement as low as possible. Nevertheless, a certain degradation during lock-in thermography cannot be avoided. As Fig. 3 shows, after this lock-in measurement the I-V characteristic is already partly but not fully degraded. Then complete degradation was obtained by 24 hrs current degradation at 120 mA. The I-V characteristic was measured again, and a second lock-in thermogram was measured at the same bias of 0.51 V, leading now to a current of 2.05 mA. Indeed, this final current-induced degradation still produced a clear current increase, as Fig. 3 shows. Of course, the second lock-in measurement did not increase the current anymore.

Fig. 4 shows the two lock-in thermograms using the same scaling factor and the image of the difference between these two thermograms. This difference image can be interpreted as the local distribution of the B-O complex, which is responsible for the degradation. Both original thermograms show two local shunts as bright spots. These shunts show a non-linear (diode-like) I-V characteristic [7]. The difference image in Fig. 4 does not show these two shunts. Hence, their signal is the same in both thermograms. This proves that the B-O complex is not responsible for the appearance of these shunts. Though the difference image in Fig. 4 is somewhat noisy, it can be concluded that the B-O complex is distributed essentially homogeneous in this small-sized sample (2x2 cm^2).

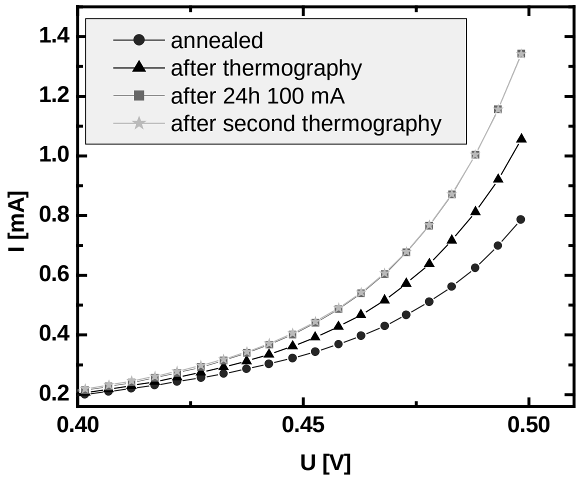

Fig. 3: I-V characteristics at different stages

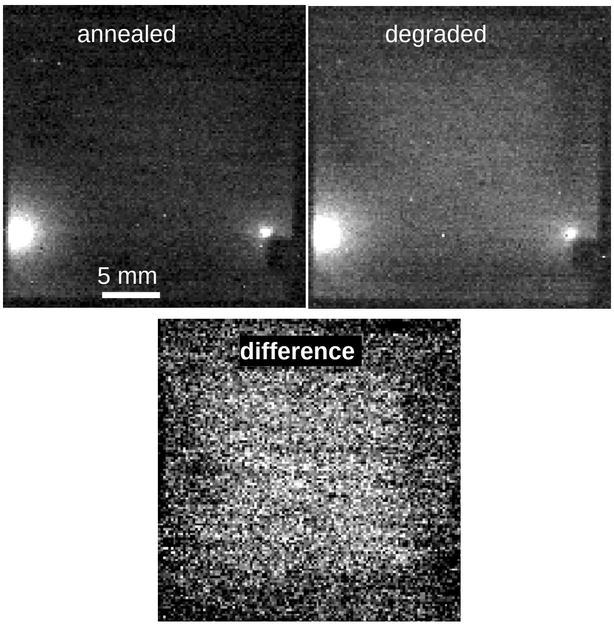

Fig. 4: Lock-in thermograms of the PERT cell before and after degradation (both scaled to 0.2 mK) and difference image (scaled to 0.05 mK)

INVESTIGATION OF THE 10x10 cm^2 CELL

For the second investigation we used a 10x10 cm^2 sized CZ solar cell fabricated at Fraunhofer ISE, which shows in LBIC so-called "striation" rings. It should be checked whether these rings are affecting the local degradation behaviour. We have repeated the same procedure as described above, which is annealing, dark IV-characteristic measurement, 1st thermography measurement, dark IV-characteristic measurement, degradation, dark IV-characteristic measurement, and 2nd thermography measurement. Fig. 5 shows all dark I-V characteristics of this cell. In this case we have performed the thermography measurements with a higher bias, but for a lower acquisition time. Though the amount of injected charge per area was comparable in both cases, we can see that the 10 min lock-in thermography at 570 mV causes a smaller increase of the dark current than shown in Fig. 3. This observation coincides with the observation that the degradation time constant is only little affected by the injection level [2, 8]. After intended current degradation (in this case 2A for 120 min.) a larger increase of the dark current was observed.

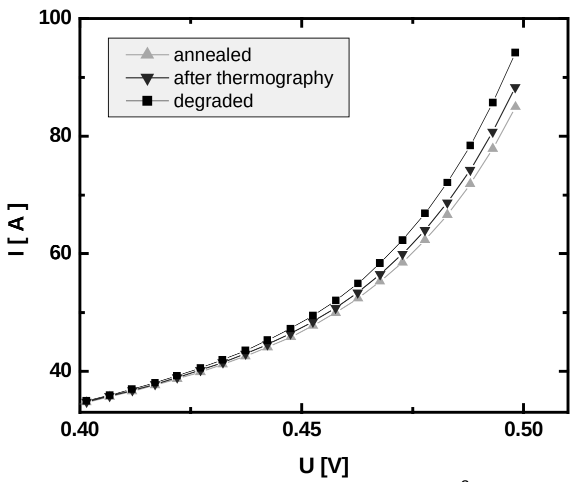

Fig. 5: Dark I-V characteristics of a 10*10 cm^2 CZ solar cell after the anneal, lock-in thermographyand after 120 min. current degradation

Fig. 6 shows the two lock-in thermograms using the same scaling factors and the image of the difference between these two thermograms. As discussed above, this difference image can be interpreted as the local distribution of the B-O complex, which is responsible for the degradation. The dark horizontal stripes at the right are the current leads to the cell. The thermogram after annealing shows some shunts in this solar cell as well as the striations rings. After degradation an increase of the injection current across the whole surface of the cell was observed, and the striations are still visible. The difference image shows that in the striation region the degradation was even somewhat smaller than in the rest of the cell. Hence, contrary to our original expectation, the striations do not show preferred current-induced degradation.

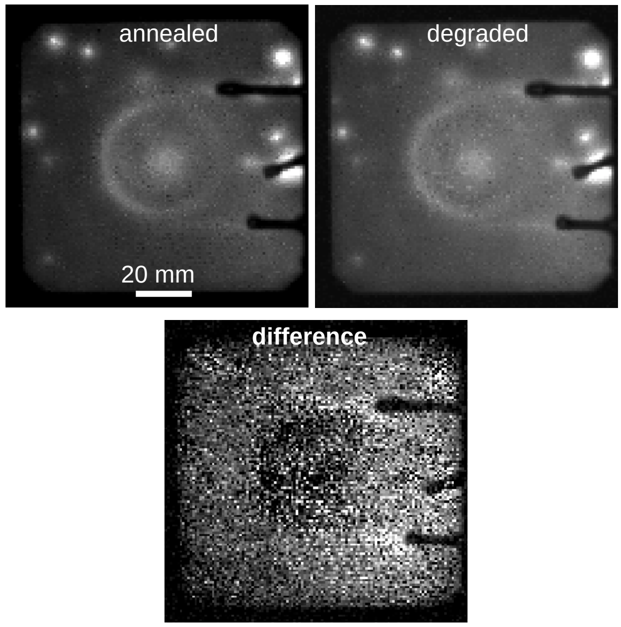

Fig. 6: Lock-in thermograms of the screen-printed cell before and after degradation (both scaled to 2 mK) and difference image (scaled to 0.2 mK)

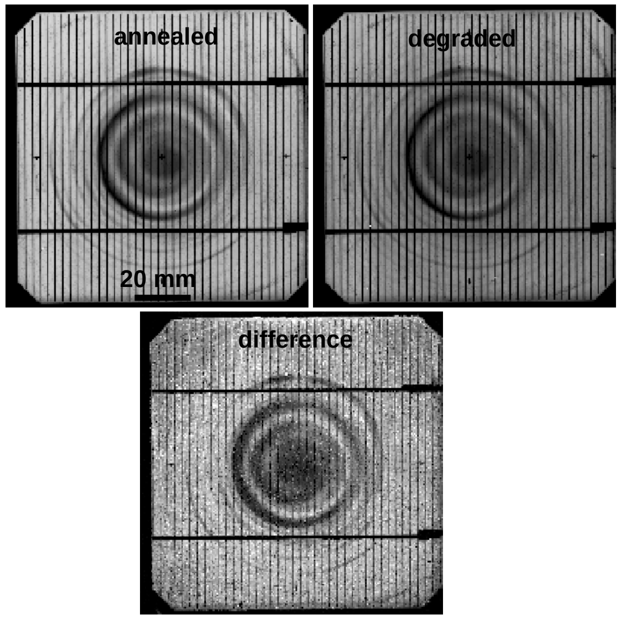

Fig. 7: LBIC images of the screen-printed cell before and after degradation (both in the same scaling) and difference image

In order to confirm this result we have performed also LBIC investigation at 760 nm wavelength (without bias light) after annealing and after degradation. The results of these LBIC investigations are presented in Fig. 7. In this case the dark I-V characteristics before and after LBIC measurement were identical, since every point of the cell was exposed to the light only for 1 second. Hence, the LBIC measurement did not induce any degradation. The striation rings are even clearer visible in LBIC than in the thermograms, and they are also visible already in the annealed state. After annealing, the general brightness of the LBIC image is reduced (indicating the degradation-induced reduction of the diffusion length), but the striations are still visible. Note that the contrast of the LBIC images was somewhat enhanced to show the striations more clearly. The maximum LBIC contrast was in the order of 20 %, but in the difference image it is about 100 %! Hence, the LBIC difference image between the annealed and the degraded state shows even more clearly than in the thermograms that in the region of the striations the degradation of short-circuit current is even smaller than in the rest of the cell. In order to calculate the density of Cz-defects quantitatively it would be necessary to determine the diffusion length variation and not only the short-circuit current reduction.

CONCLUSIONS

It has been shown by lock-in thermography and LBIC imaging that the current-induced degradation (which is equivalent to the light-induced one) both of a 2x2 cm^2 PERT and a 10x10cm^2 solar cell is essentially homogeneous across the cell area. Obviously the striations, which are visible in the 10x10cm^2 cell in LBIC and also in lock-in thermography, seem not be directly correlated with the observed degradation. In opposite, in the striation regions the degradation of short-circuit current was even smaller than in the rest of the cell. Thus, if the microscopic origin of the striations would be clear, this could give another hint on the microscopic nature of the B-O complex, which should be responsible for the degradation of CZ solar cells.

Acknowledgements

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