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Impact of micro-cracks on the degradation of solar cell performance based on two-diode model parameters

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Abstract

Electroluminescence (EL) imaging technique has become a powerful and fast characterization tool providing spatially-resolved information about electrical, optical and material properties of solar cells. When applying a forward bias the solar cell emits infrared radiation whose intensity is governed by the minority carrier lifetime in the bulk and thus decreases considerably in the vicinity of intrinsic defects and cracks. In this work the influence of micro cracks and the progression of already existing cracks in multicrystalline silicon solar cells are investigated. The impact of these defects on the electrical solar cell parameters is studied in the frame of the two-diode model. Statistically proven, it was found that beside a decrease in EL intensity the short circuit current J_{sc} and the efficiency η also will be reduced, whereas a strong increase in the recombination current density j_{02} is observed. This work on crack detection and the research on crack-forming will help to explain the reasons behind the loss of efficiency seen in long-term performance analyses.

Keywords: micro-cracks; multicrystalline silicon; electroluminescence

1. Introduction

Electroluminescence-imaging is a quick and easy method to analyse qualitatively the material quality of processed solar cells and to detect micro-cracks during solar cell and module production [1-4]. Different types of process steps generate extrinsic defects due to mechanical loads or heat effects [5]. With the aid of fast inline crack detection damaged cells can be sorted out. Just as during the processing, cracks are formed as well in finished modules through external factors of mechanical origin. A resulting

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loss in module output power was frequently observed e.g. [4,6]. This work intends to clarify the background of those effects by a controlled generation of micro-cracks in standard multicrystalline silicon solar cells, their detection and visualisation with the aid of electroluminescence-imaging and the analysis of their impact on electrical cell parameters. Furthermore the investigation is made with two sample groups of different material quality. Thereby the effects of micro-cracks on electrical cell parameters are proven to be material independent.

2. Experimental setup and data acquisition

For an easy and quantitative analysis of micro-cracks in multicrystalline silicon solar cells it is important to find a reliable solution to generate micro-cracks in a well-controlled manner. For this purpose mechanical edge isolation with varied contact pressure parameters was chosen. Making use of the EL images taken before and after the isolation process step the new generated micro-cracks become clearly visible in a quotient image (figure 1). In this calculated image the "after" image is divided by the "before" image pixel by pixel. A cooled Si-CCD camera and a constant forward bias of 9.6 mA/cm^2 were used.

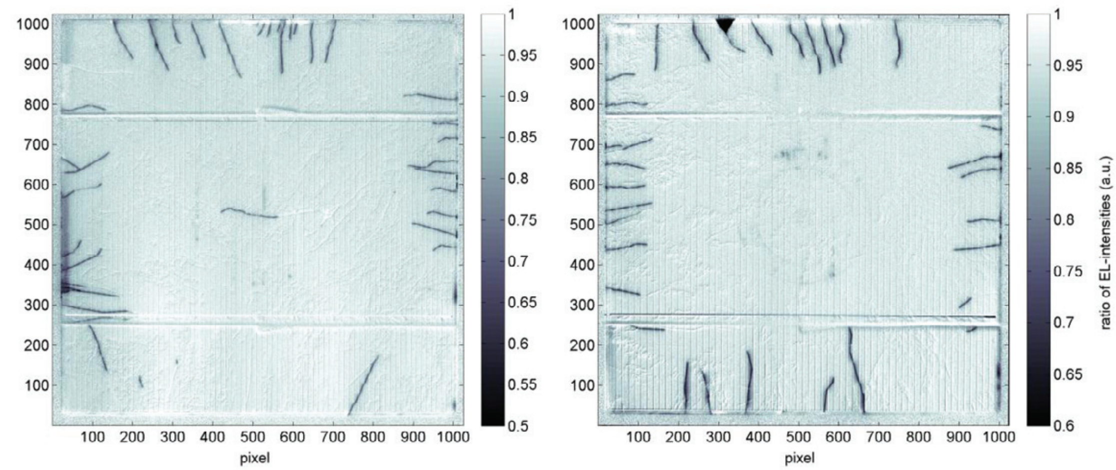

Fig. 1. Two ratio images of EL intensity after and before the mechanical edge isolation process step; generated micro-cracks become clearly visible by a decrease in electroluminescence intensity and thus a quotient lower than 1. Strong cracks show a decrease in electroluminescence intensity of up to 50 %. In those regions the local minority carrier diffusion length is reduced approximately by the same factor

As can be seen in figure 1 propagated already existing micro-cracks (center of the left image) as well as additionally induced micro-cracks (edge area of both cells) occur. By means of this method micro-cracks were induced in a group of 39 identically processed standard multicrystalline p-type solar cells with two different material qualities. The sample size was 156.25 cm². Below, the sub-group with higher material quality is named M1, the other one M2. The 23 cells in group M2 show a much higher density of sub-grain boundaries (figure 2).

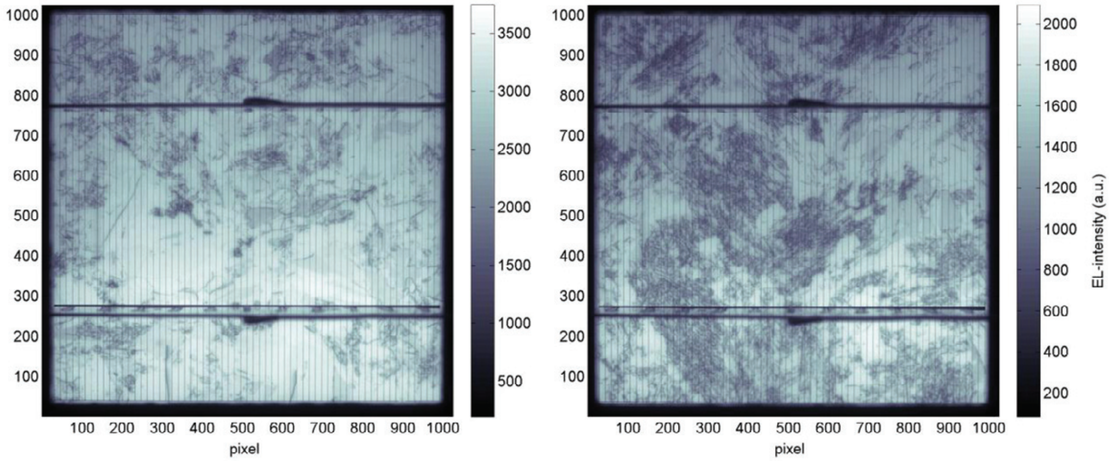

Fig. 2. Comparison of cell group M1 (left) and M2 (right): Shown is a sample EL-image from each group, respectively. The samples of cell group M2 show a higher density of sub-grain boundaries than the samples of group M1. Furthermore the measured peak EL-intensity as well as the summed up EL-intensity of all camera pixels reveals large differences. The summed up intensity of group M1 is 1.8 ± 0.1 times larger than those of group M2, averaged over all samples of each group

To investigate the impact of the induced mechanical defects, before as well as after the isolation step, illuminated I-V-characteristics under standard test conditions were measured. The external electrical parameters short circuit current J_{sc}, the open circuit voltage V_{oc}, the fill factor FF and the cell-efficiency η are directly obtained from the characteristic curve. Furthermore, the measured data are fitted to the two-diode model to calculate the internal electric parameters j_{01}, j_{02}, j_{ph}, R_s and R_p in a reliable way [7].

3. Results

The EL-images in figure 2 reveal large optical differences between both cell groups M1 and M2. To analyse both cell groups regarding their electrical characteristics illuminated IV-measurements were made. The results are shown in table 1 and table 2.

Table 1 illustrates the calculated mean values of the external electrical cell parameters separately for material group M1 and M2 before the crack formation. Ratios and differences of these parameters are provided as well.

Table 1. Influence of material quality on external cell parameters

	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
mean value (M1)	33.0 ± 0.1	617 ± 2	78.7 ± 0.5	16.0 ± 0.1
mean value (M2)	32.7 ± 0.1	601 ± 1	78.1 ± 0.2	15.3 ± 0.1
	quotient M1/M2 (%)		difference M1-M2 (%)	
	1.1 ± 0.4	2.5 ± 0.3	0.6 ± 0.5	0.7 ± 0.1

Within the bounds of the statistical errors in J_{sc}, V_{oc} and η there is a strong wafer material dependency of up to 2.8 % in V_{oc} and 0.8 % absolute in η. Similarly table 2 shows the mean values of the internal electrical parameters of both cell groups.

Table 2. Influence of material quality on internal cell parameters

	j_{01} (pA/cm^2)	j_{02} (nA/cm^2)	j_{ph} (mA/cm^2)	R_s (Ωcm^2)	R_p (kΩcm^2)
mean value (M1)	0.94 ± 0.06	32 ± 3	33.0 ± 0.1	0.31 ± 0.02	1.7 ± 0.5
mean value (M2)	1.71 ± 0.04	41 ± 2	32.6 ± 0.1	0.40 ± 0.03	2.6 ± 0.4
			quotient M1/M2 (%)		
	-45 ± 4	-21 ± 8	1.2 ± 0.4	-20 ± 10	-30 ± 20

In the recombination current density j_{02} and most notably in the diffusion current density j_{01} there is a strong influence of the material quality. The recombination current densities are up to 96 % higher in the cells with reduced material quality due to a higher density of impurities and grain boundaries. Furthermore, the photo current density j_{ph} gets affected showing a 1.2 ± 0.4 % higher value in group M1. This is also in accordance with the difference in measured J_{sc} values of both groups as shown in table 1. Additionally, the difference in material quality can be clearly distinguished examining the series resistances.

Having analysed the differences between the two used groups considering the external and internal electrical parameters, micro-cracks were induced as explained in section 2. For this investigation all samples of above mentioned cell groups were used. The ratio and difference, respectively, of each cell parameter after the formation of micro-cracks was calculated. A decrease in EL intensity, hence a ratio smaller than 1 in the quotient image, is equivalent to a decrease of the local minority carrier diffusion length in the bulk under certain assumptions [8]. Regarding figure 1 it can be stated that the diffusion length is reduced locally due to the generated micro-cracks down to approximately 50 %. This observation can be explained investigating the electrical parameters of the solar cells. Table 3 and table 4 deal with the impact of these induced micro-cracks on the electrical cell parameters.

Table 3. Impact of generated micro-cracks on external cell parameters

relative change in J_{sc} (quotient) (%)	relative change in V_{oc} (quotient) (%)	absolute change in FF (%)	absolute change in η (%)
-0.4 ± 0.1	-0.2 ± 0.2	-0.3 ± 0.3	**-0.17 ± 0.06**

Induced extrinsic defects cause a decrease in J_{sc} as well as in η by 0.4 ± 0.1 % and 0.17 ± 0.06 % absolute, respectively. Although the micro-cracks cover a negligible part of the cell surface, they have a remarkable influence on the cell efficiency. Furthermore, V_{oc} and FF show a reduction, too, but their decrease lies within the range of their statistical errors. These impacts of the micro-cracks were investigated further in detail by means of the internal cell parameters listed in table 4.

Table 4. Impact of generated micro-cracks on internal cell parameters

rel. change in j_{01} (%)	rel. change in j_{02} (%)	rel. change in j_{ph} (%)	rel. change in R_s (%)	rel. change in R_p (%)
2 ± 5	**22 ± 9**	**-0.4 ± 0.1**	3 ± 4	14 ± 17

There is a strong increase in j_{02} by 22 ± 9 %. The second diode is used for the modelling of recombination in the space charge region [7]. That is why the increase in j_{02} is a strong evidence for newly generated recombination centres through micro-cracks. The ideality factor of the second diode was kept constant at n=2. To further support the observed behaviour, together with the aid of Dark Lock-in Thermography (DLIT) it is shown that micro-cracks are acting primarily as recombination centres, since a local increase in temperature occurs in defect locations (figure 2) [9]. For this investigation a standard turn-key DLIT-imaging tool under a forward excitation current density of 9.6 mA/cm^2 was used.

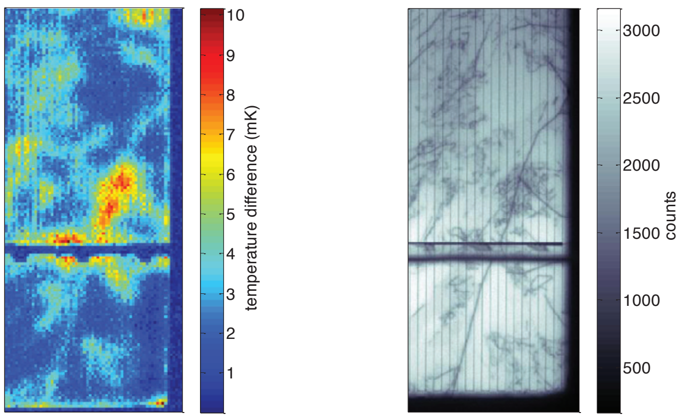

Fig. 2. (left) DLIT image of a section of a solar cell with large micro-crack; (right) EL image of the same section and identical excitation conditions for comparison; micro-cracks are detectable with both imaging systems

Table 4 also reveals a decrease in j_{ph}. Micro-cracks are inactive cell domains and thus reduce the active cell area by ΔA. To fit the decrease in j_{ph} by 0.4 ± 0.1 % as seen in table 4 with the two-diode model, the measured J_{sc} value gets normalized by the full wafer area by default. Thereby a possible area change is disregarded. Hence it is possible to calculate the loss area ΔA with the aid of the relative change in j_{ph}. A calculation of ΔA on different samples based on the number, length and width obtained from REM-images (not shown here) of the micro-cracks fits well with the decrease observed in j_{ph}.

The impact of extrinsic defects is less significant on j_{01} and the resistances R_s and R_p owing to generally low values of R_s and high values of R_p of all used cells. All observations are valid for both cell groups, M1 and M2, hence indicating the independency of material quality of this approach.

4. Conclusion

Micro-cracks acting as electrical recombination centres have been analysed concerning their impact on different electrical solar cell parameters. This work provides the background for the observation of a decrease in J_{sc} and η and explains the increase in j_{02} in field studies of solar module degradation e.g. [6]. Special care must be taken in the analysis of long-term degradation mechanisms taking the analysed and shown effects of micro-cracks into consideration.

Acknowledgements

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References

[1] Fuyuki T, Kondo H, Yamazaki T, Takahashi Y, Uraoka Y. Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescence. *Applied Physics Letters* 2005;**86**:262108.

[2] Rau U. Reciprocity relation between photovoltaic quantum efficiency and electroluminescent emission of solar cells. *Physical Review* B 2007;**76**:085303

[3] Sugimura E, Tsujii S, Hirata K, Tani A, Fuyuki T. Distinction of crystal defects by temperature dependence of electroluminescence. *Proceedings of the 25th European Photovoltaic Solar Energy Conference*, Valencia, 2010, p. 2554-2557

[4] Demant M, Rein S, Krisch J, Schoenfelder S, Fischer C, Bartsch S et al. Detection and analysis of micro-cracks in multi-crystalline silicon wafers during solar cell production. *Proceedings of the 37th IEEE Photovoltaic Specialists Conference*, Seattle, 2011.

[5] Kajari-Schröder S, Kunze I, Eitner U, Köntges M. Spatial and orientational distribution of cracks in crystalline photovoltaic modules generated by mechanical load tests. *Solar Energy Materials & Solar Cells* 2011;**95**:3054-3059.

[6] Mabille L, Razongles G, Sicot L, Merten J. Performance Analysis of Crystalline Silicon PV Modules after 18 Months Exposure under Tropical Climate. *Proceedings of the 26th European Photovoltaic Solar Energy Conference,* Hamburg; 2011, p. 3491-3494.

[7] Suckow S, Pletzer T M, Kurz H. Fast and reliable calculation of the two-diode model without simplifications. *Progress in Photovoltaics: Research and Applications* submitted

[8] Fuyuki T, Kondo H, Kaji Y, Ogane A, Takahashi Y. Analytic findings in the electroluminescence characterization of crystalline silicon solar cells. *Journal of applied Physics* 2007;**101**:023711.

[9] Breitenstein O, Warta W, Langenkamp M. *Lock-In Thermographie: Basics and Use for Evaluating Electronic Devices and Materials.* Berlin: Springer-Verlag; 2010