EL/PL imaging, breakdown analysis and series resistance of silicon solar cells

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Application Note

Introduction
In general luminescence is used to visualize defects in solar cells, which are invisible to the human eye but limit the carrier lifetime, so the efficiency of the solar cell. Using luminescence pictures defects can be determined, serial resistance pictures can be calculated, by applying a reverse voltage it is possible to investigate breakdown behaviour of solar cells, and, by implication, the manufacturing process can be optimized too.

Measurement Set-up
Luminescence means the radiative band-to-band- recombination of induced electrons. Since silicon has a band gap energy of E_{gap}=1.1 eV the luminescence signal is to be expected at wavelength of 1100 nm. Therefore a camera is needed, which can detect photons between 1000 nm and 1200 nm wavelength as well an objective with high transmission in this range, to image the luminescence of a silicon solar cell. The Andor iKon-M PV-Inspector DU934P-CSV-BR-DD with an Qioptiq inspec.x M NIR objective fulls this requirement. There are two ways to image solar cells by means of luminescence:
i) electroluminescence (EL), i.e. applying a voltage to the cell
ii) photoluminescence (PL), i.e. exciting of the carriers by light. Furthermore by applying a reverse voltage to the cell breakdown sites can be imaged,[1] which is named ReBEL (reverse bias EL).[2] The measurement set-up for both is shown in Figure 1.

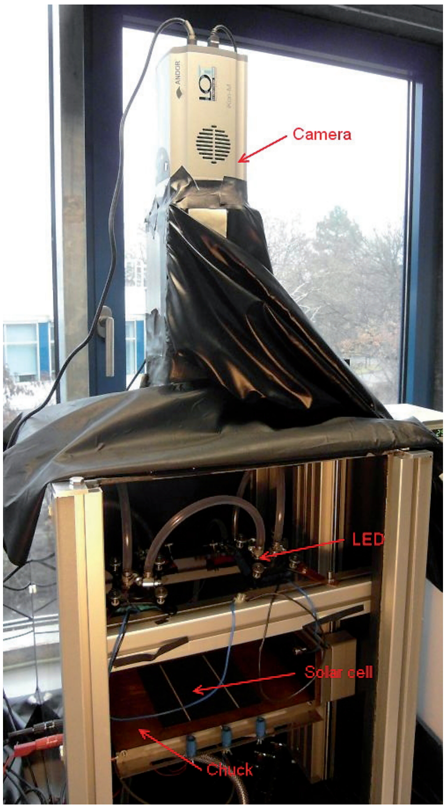

Figure 1: Measurement set-up with camera, water-cooled LEDs and stage for the solar cell in a dark chamber

Electroluminescence (EL)
EL is only possible with contacted solar cells, since the electrons are induced by an external applied voltage, which can be a forward or a reverse bias. To eliminate external influences, the experimental set-up is in a dark chamber and the solar cell lies on a cooled table. The table also provides the rear contact of the cell, while the front is contacted via contact-bars.

The advantage of EL in comparison to PL is that the solar cell is the only light source and so no additional filter system is needed and also a reverse bias could be applied.

Photoluminescence (PL)
As mentioned above PL works with a light source to excite electrons from the valence band to the conduction band. To do so the light has to be of a shorter wavelength than the luminescence signal. The second requirement is, that the initial light source is not to be seen at the luminescence image of the camera, so depending on the light source, a complex filter system is needed. In this set-up four high power LED-arrays of 850 nm wavelength are used for illumination, which could be found in Figure 1. In front of the LEDs short-pass filters with a cut-off wavelength of 870 nm suppress the tail LED-light to the longer wavelengths, which would interfere the luminescence signal. To prevent the camera from capturing the LED-light there are also two 1000 nm long-pass filters with an optical density of four mounted in front of the camera. The advantage of PL is, that also wavers could be examined, due to the contactless excitation of electron hole pairs.

Examples
A PL image is shown in Figure 2. Compared with the EL-image (Figure 3), there is no additional luminescence around the contact bars of the solar cell, because of the contactless excitation of electrons, which is due to illumination more homogeneous than applying an external voltage at the contact bars. Red encircled is a region with shunts.

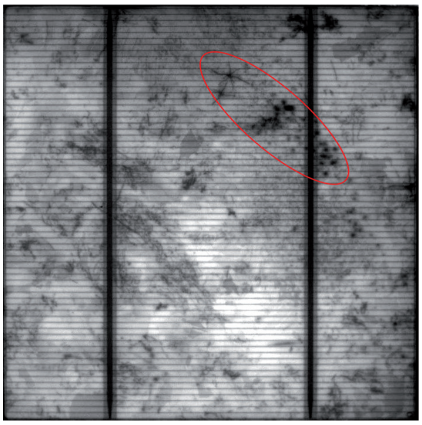

Figure 2: PL image (exposure time: 500 ms)

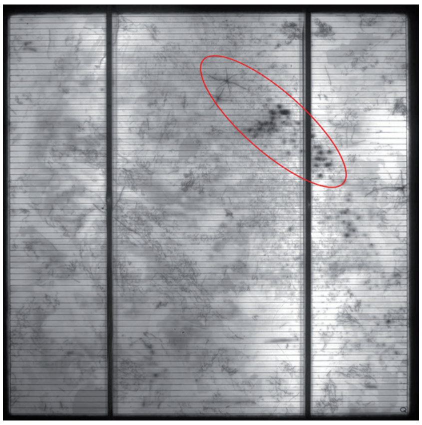

Figure 3: EL image (forward bias of 600 mV ; exposure time: 10 s)

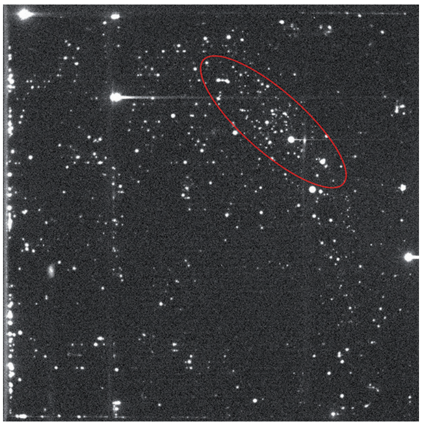

Figure 4: EL image (reverse bias of -10 V ; exposure time: 30 s)

The same cell as in Figure 3 is also pictured in Figure 4, but with reverse bias applied. The bright spots are breakdown sites. This kind of images can help to characterise the type of defects in a solar cell, which sometimes could be difficult only regarding the forward bias image.[3] The dark areas in Figs. 2 and 3 are dislocations, grain boundaries, or other cristallographic defects affecting the carrier lifetime.

Series Resistance Imaging

Another possibility of luminescence is series resistance imaging, where the series resistance R_s is calculated from two EL images with different applied biases and a background image without applied voltage.[4] An R_s-image is shown in Figure 5. The series resistance takes its lowest values at the contact bars, because of the shortest way for the carriers.

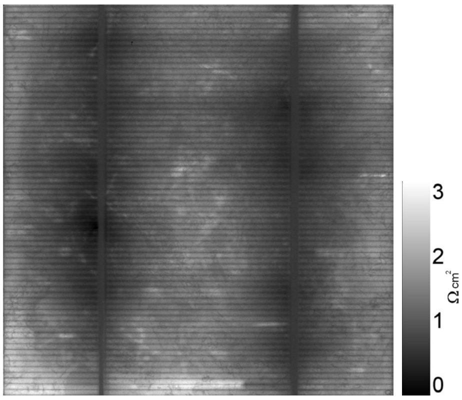

Figure 5: R_s-image calculated from 590 mV and 560 mV EL-image; calibration bar is in Ωcm²

Conclusion

Camera-based luminescence imaging is an effective method to examine cells or wafers (in case of PL). Defects as well as breakdown sites and series resistance images derived from such luminescence images help to characterise silicon solar cells in industry and research.

References

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[3] Otwin Breitenstein, Jan Bauer, Karsten Bothe, Wolfram Kwapil, Dominik Lausch, Uwe Rau, Jan Schmidt, Matthias Schneemann, Martin C. Schubert, Jan-Martin Wagner, and Wilhelm Warta, "Understanding junction breakdown in multicrystalline solar cells", J. Appl. Phy. 109, 071101 (2011), DOI: 10.1063/1.3562200

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