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Leakage of photocurrent: an alternative view on I–V curves of solar cells*

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Abstract: An alternative way is proposed to interpret I–V characteristics of GaInP single-junction solar cells by position-dependent leakage of photocurrent. With this approach, the I–V curves of solar cells under non-uniform illumination are well analyzed. The effective spreading resistance is also extracted to understand the dynamic behavior of between the open-circuit voltage and short-circuit current points. The conditions under which the one-diode model will fail are addressed in detail. These analyses are also applicable for a characterization of the I–V curves with lateral voltage distribution under uniform illumination.

Key words: GaInP single-junction solar cells; I–V characteristics; open-circuit voltage

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1. Introduction

Current–voltage (I–V) characteristic indicates the performance of a solar cell. Usually, the one-diode model[1] or two-diode model[2] is used to extract device parameters from I–V curves. Intrinsically, the two models are identical. They treat the P–N junction as a diode, the leakage path as a shunt resistance and the series resistance as a lumped one. Due to its simplicity and capability of explaining most I–V curves, the one-diode model has been mostly investigated and utilized[3, 4]. A solar cell is a two-dimensional device with lateral current spreading effects[5, 6], so the one-diode model may fail under some conditions. As an example, it cannot tell why the ideal factor increases with concentration ratio[7]. What is worse, the one-diode model can be misleading at sometimes. For example, the slope of I–V near the short circuit region is usually interpreted as a leakage path and treated with a shunt resistance. Simulations have been performed based on a three-dimensional circuit model which take the current spreading effects into consideration[8]. Still, the physics mechanism behind the device is not well explored. To recognize the current spreading or leakage path in the solar cells, such as concentration photovoltaic (CPV)[9], InGaN solar cell[10] and dye-sensitized solar cell (DSSC)[11], a more detailed investigation of the I–V curves is necessary. In this article, a developed model on the basis of the conventional one-diode model is proposed, in which the position-dependent leakage of photocurrent is considered.

2. Physical model

For a solar cell shown in Figure 1(a), the anode covers the whole back surface while the cathode is located on the front surface. There are vertical currents across the space charge region (SCR) and lateral current I above the SCR. Figure 1(b) shows the equivalent circuit model of the device. The point C stands for the bus region of the cathode, and the point D corresponds to the region far away from the bus on the front surface of the solar cell. Similar to a one-dimensional P–N junction, the local vertical current $j(r)$ can be expressed as[12]

$$j(r) = j_{\text{ph}}(r) - j_{\text{lk}}(r), \tag{1}$$

where r is position-dependent variable, $j_{\text{ph}}(r)$ and $j_{\text{lk}}(r)$ is the local photocurrent and leakage current as shown in Figure 1(a), respectively. The photocurrent is dependent on local light intensity $I_{\text{ph}}(r,\lambda)$ and external quantum efficiency (EQE).

$$j_{\text{ph}}(r) = \int I_{\text{ph}}(r,\lambda)\text{EQE}(\lambda)\text{d}\lambda, \tag{2}$$

where λ is the wavelength of an incident light. The leakage current flows through the diode shown in Figure 1(b), so it depends on the local voltage as

$$j_{\text{lk}}(r) = j_{\text{lk}}(V(r)). \tag{3}$$

The terminal current I_t under voltage V_t is the total current

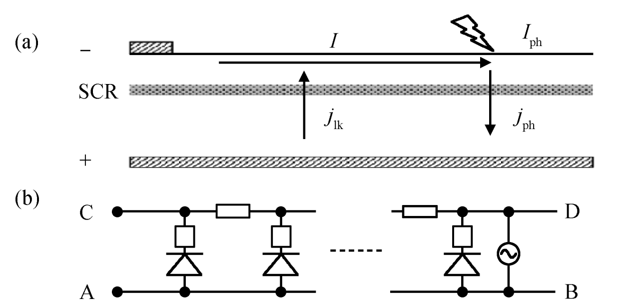

Figure 1. (a) Schematic diagram of a solar cell. (b) Equivalent circuit model of the device.

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across the whole device. It can be expressed as

$$I_t(V_t) = \int j\,\mathrm{d}r. \tag{4}$$

Substitute Equation (1) into Equation (4),

$$I_t(V_t) = I_G - I_{Leakage}(V_t), \tag{5}$$

where I_G and $I_{Leakage}$ are

$$I_G = \int j_{ph}(r)\mathrm{d}r, \tag{6}$$

$$I_{Leakage} = \int j_{lk}(V(V_t, r))\mathrm{d}r. \tag{7}$$

Note that Equation (5) has a similar form to the one-diode model, which is expressed as[11],

$$I_t = I_{SC} - I_0\left(\exp\frac{V_t + I_t R_S}{mV_{th}} - 1\right) - \frac{V_t + I_t R_S}{R_{SH}}, \tag{8}$$

where I_0, R_S, R_{SH}, m, V_{th} are reverse saturate current, lumped series resistance, shunt resistance, ideal factor, and thermal voltage, respectively. Under the special condition when the voltage $V(r)$ is uniform over the whole device, this model is identical to the one-diode model.

In an actual device, there is always non-uniformity of lateral voltage $V(r)$[13]. In Figure 1(b), the local photocurrent j_{ph} is represented by a current source. The sheet resistance above the SCR is represented by resistance. When the photocurrent flows from point D to point C, there is a voltage drop between the two points. The ohmic relationship is

$$V_{CD} = I_{CD}R_{CD}, \tag{9}$$

where I_{CD} and R_{CD} are effective lateral current and spreading resistance, respectively. Both are dependent on the device structure. Additionally, I_{CD} is dependent on the light $I_{ph}(r, \lambda)$. As the anode covers the whole back surface, no voltage drop between points A and B can be assumed. Correspondingly the voltage at point D can be expressed as

$$V_{BD} = V_{AC} + V_{CD}. \tag{10}$$

Then, the leakage current at point D can be determined by local junction voltage V_{BD}.

So far, three properties of I–V can be obtained based on the above analysis. They are listed as follows.

(a) The short-circuit current $I_{SC} = I_G$, if $I_{Leakage} = 0$ when $V_t = 0$. It means the I_{SC} does not depend on the illumination distribution $I_{ph}(r, \lambda)$.

(b) The leakage current is dependent on illumination, device structure and electrodes.

(c) Due to the lateral voltage distribution, given specific terminal voltage, the leakage current is usually larger for the non-uniform illumination than the uniform illumination. The open circuit voltage (V_{OC}) may fall compared to the uniform illumination condition.

Although the property (c) holds in most cases[14, 15], it might be incorrect at some extreme cases. For example, if the spreading resistance is abnormally large, compared to the uniform illumination, the light illumination near the cathode may generate a larger V_{OC}. Ignoring the unusual case, these properties will be further explored.

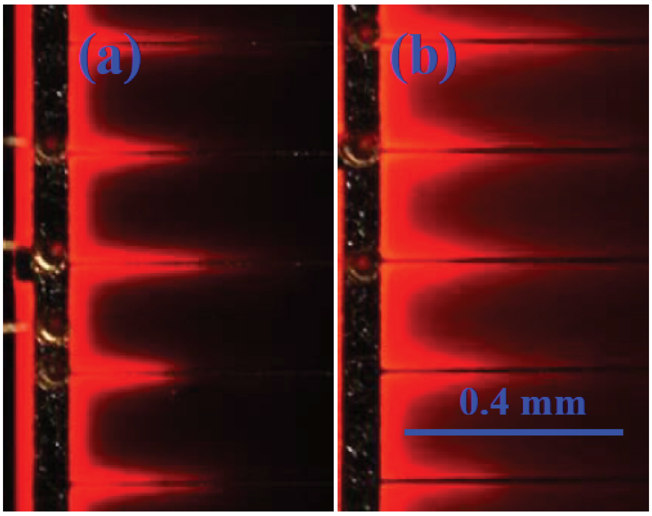

Figure 2. Electroluminescence images of samples (a) A and (b) B. The bias current is 50 mA.

3. Experiments

The two GaInP solar cells investigated are grown simultaneously on different GaAs substrates with misorient angle of 2° and 9°, respectively. They will be referred to as samples A and B. The dimension of the cells is 2.6 × 2.6 mm^2. There are a bus and a few finger electrodes on the front surface, which are fabricated with different techniques for one-sun illumination. Figure 2 shows the electroluminescence (EL) images of the cells under bias current of 50 mA. The non-uniform light distributions indicate there are current spreading effects in both cells[6, 13]. A close view of the images reveals that the effective spreading resistance of sample A is larger than that of sample B. To measure the I–V curves, a steady AM 1.5 G simulator is used as light source. A fresnel lens is used to concentrate the light into a small spot. During the measurement, the cell will be placed near the focus of the lens. By changing the optical aperture, the concentration ratio can be adjusted while the light distribution does not vary too much. Several I–V curves at different illumination levels are shown in Figure 3. The illumination intensity increases from a to e. It can be seen that there exists serious performance degradation under concentration for both cells.

4. Parameters of solar cell

To further evaluate the performance, the V_{OC} and fill factor (FF) are extracted and shown in Figure 4(a). It seems that V_{OC} is linear to the logarithm of I_{SC} and FF falls because of series resistance. Both of the trends can be explained well with the one-diode model. Furthermore, reverse-saturate current and ideal factor m, which indicates the features of a P–N junction[2], are shown in Figure 4(b). The reverse-saturate currents are extraordinarily large for both samples. It can be seen that there exists a remarkable difference between the ideal factors of the two samples. Besides, as concentration ratio increases, the difference becomes larger, which cannot be understood by a P–N junction model. Because all these parameters are used frequently in the research of various solar cells, it is important

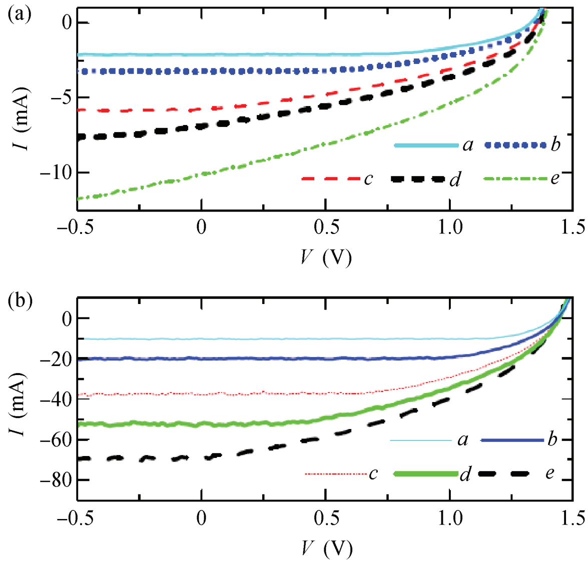

Figure 3. (Color online) Typical I–V curves of sample (a) A and (b) B. The illumination distribution remains unchanged while the intensity increases from a to e.

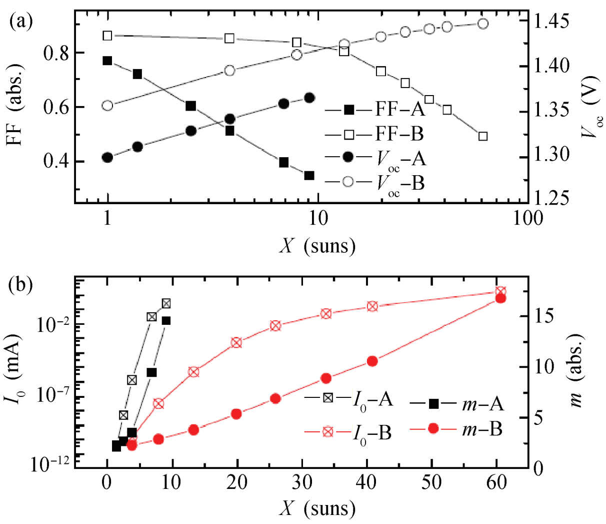

Figure 4. (Color online) Extracted parameters for one-diode model from I–V curves. (a) Fill factor and open circuit voltage. (b) Reverse-saturate current and ideal factor.

to understand the physics mechanism behind them.

In the above analysis, it can be found that there will always be non-uniform voltage distribution $V(r)$ due to the lateral current. This non-uniformity together with the exponential I–V of P–N junction will cause a complicated V_t-dependent-leakage current and thus affects the I–V curve of solar cell. In the case of the two cells under investigation, the position-dependent leakage current has a profound influence on the cell performance.

5. Leakage current

To reveal how the non-uniform illumination influences the leakage current, two I–V curves of sample A are shown in Figure 5. The calculated I–V curve is obtained using Equation

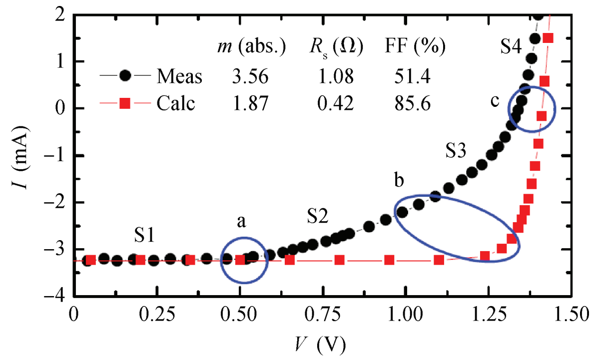

Figure 5. (Color online) Measured I–V characteristics of sample A and one calculated using one-diode model with parameters extracted from dark I–V. Each curve is divided into four sections (S1 to S4) by three transit regions (a, b and c).

(8) with parameters extracted from the dark I–V. The dark I–V is not seriously affected by current spreading, so the calculated I–V is adopted as a reference for the measured one. The parameters are also shown. The I_{SC} are the same, according to Equation (5), it is leakage current that decides the shape of I–V. To analyze the trend of leakage current with increasing terminal voltage, the I–V curves are divided into four sections by three transit regions, i.e., a, b and c in Figure 5. In section S1, $I_{Leakage} = 0$, so $I_t = I_G$. In region a, the increase of $I_{Leakage}$ of measured I–V starts, which results in a reduction of I_t. In region b, the output power is maximized. $I_{Leakage}$ of measured I–V near the region is observed in a linear shape and $I_{Leakage}$ of calculated I–V starts to increase. In region c, the V_{OC} is reached and the two I–V curves become alike, which may indicate the same current leakage mechanism.

For the configuration of Figure 1(b), the voltage is lower at the light spot D than the one at the point C according to Equation (9). So, the leakage current at D is larger than that near the cathode. It is interesting that on one hand, the light spot generates photocurrent, on the other, it also induces leakage current. The local leakage current j_{lk} is dependent on local voltage $V(r)$, whose j–V characteristic is similar to that of a diode. Supposing the leakage current starts to increase remarkably at the cut-in voltage V_{cut}, the following relationship can be established for region a using Equations (9) and (10).

$$V_c + I_{CD}R_{CD} = V_{cut}. \tag{11}$$

It means that there is a critical terminal voltage V_c, at which the leakage current of the device starts to increase remarkably. In section S1, the terminal voltage $V_t < V_c$, so the observed I–V is flat. In sections S2 and S3, the leakage current increases linearly with V_t. Because the spreading resistance R_{CD} is serially connected with the leakage diode BD shown in Figure 1(b), it is possible that the R_{CD} limits leakage current in this voltage range. The linear shape of I–V will increase the ideal factor m and reduce the fill factor FF. In the region c, the leakage current of the measure I–V is larger, so the V_{OC} at which $I_{Leakage} = I_{SC}$ is smaller. In section S4, V_t is larger than V_{cut}. So the P–N junctions near the cathode start to contribute to the leakage current, and the terminal current increases faster.

According to Equation (11), the critical terminal voltage V_c depends on both the effective spreading current and effective

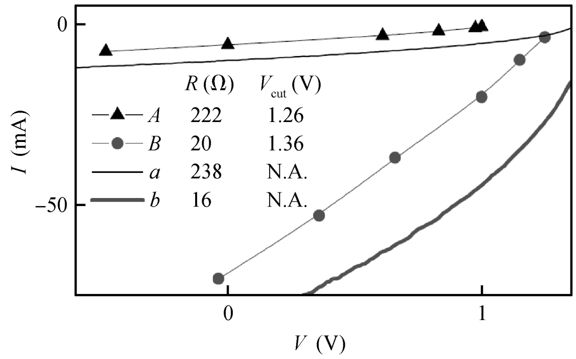

Figure 6. Short-circuit current versus the critical terminal voltage (see region a in Figure 5) and I–V for samples A (A, a) and B (B, b).

spreading resistance. In the following sections, the illumination level-dependent as well as distribution-dependent I–V will be investigated.

6. Illumination level-dependent leakage

Usually, the short-circuit current is proportional to the illumination level. Assuming the effective spreading current I_{CD} is proportional to I_{SC}, Equation (11) suggests that the V_{c} will be linear to the I_{SC}. Extracting data from the region a of I–V curves partly shown in Figure 3, the (V_{c}, I_{SC}) curves are obtained and shown in Figure 6. The region b of an I–V curve is plotted for each sample, too. It is noted that V_{c} is approximately linear to the I_{SC}. Additionally, the (V_{c}, I_{SC}) curves are nearly parallel to the measured I–V, which suggest that the spreading resistance R_{CD} dominates the I–V in region b. By linearly fitting the curves, the value of effective spreading resistance and cut-in voltage are extracted and shown in Figure 5. According to Figure 3, the cut-in voltages' values are quite reasonable.

7. Illumination profile dependent leakage

For another condition, if the distance between the light spot and the cathode bus increases, the effective spreading resistance R_{CD} becomes larger. In a similar way, the critical terminal voltage V_{c} will decrease. To measure the illumination-position-dependent I–V, a steady light strip with spot size of about 2.5 × 0.25 mm^2 is used as light source. During the measurement, the length side of light strip is perpendicular to the finger electrodes shown in Figure 2. Figure 7(a) shows the measured I–V curves. As the light spot moves far away from the bus electrode, the performance of the cell degrades. The short-circuit current remains unchanged and the V_{c} falls. Using the cut-in voltage shown in Figure 6, the effective spreading resistance is calculated from V_{c} and shown in Figure 7(b). By linearly fitting the position-dependent resistances, the resistance per distance ρ is obtained for both samples, shown in Figure 7(b). For the size of the measured solar cells (2.6 × 2.6 mm^2), these obtained ρ values are consistent with the ones shown in Figure 6.

The critical voltage point reveals some information of sheet resistance of the solar cells and the shape of I–V near maximized-power-output region is also influenced by the sheet resistance. The V_{OC} reduces as the light spot moves away from

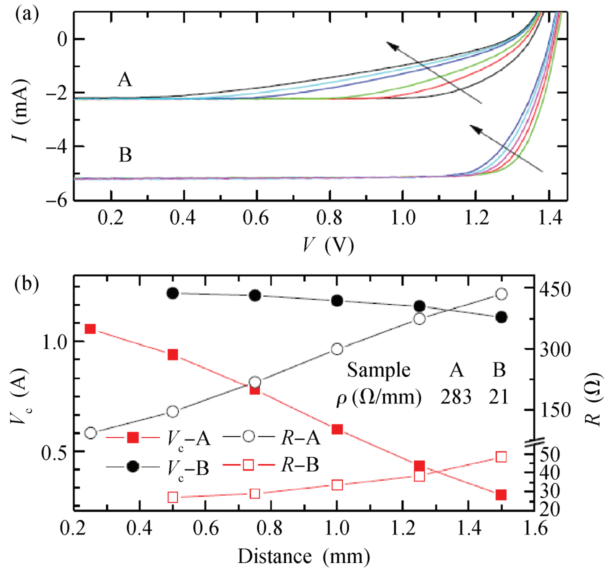

Figure 7. (Color online) (a) Illumination-position-dependent I–V curves of samples A and B. The arrows indicate the distances between the light strip and the bus electrode increase for each I–V curve. (b) Critical terminal voltage and effective spreading resistance extracted from the I–V curves in (a). The resistance per length (ρ) is obtained by a linear fitting to the effective spreading resistance.

the bus electrode. Fortunately, it increases with illumination intensity if the light distribution keeps constant. The ideal factor increases and the fill factor decreases with illumination level and non-uniformity.

8. Effective shunt resistance

It is possible that the V_{c} is negative with large absolute value that the I–V of solar cells is in the shape of I–V curve *e* in Figure 3(a). In this situation, the actual short circuit current cannot be obtained by fitting the I–V curve. Two misunderstandings of the I–V curve will occur. Firstly, the fitted I_{SC} is not proportional to illumination level any more; secondly, the curve is so sloped that there is a serious shunt resistance effect. It might avoid this problem by extending the measurement voltage range to include the V_{c}. However, at particular condition, the problem cannot be solved.

$$V_{\mathrm{breakdown}} + I_{\mathrm{CD}} R_{\mathrm{CD}} = V_{\mathrm{cut}}. \tag{12}$$

Equation (12) means the V_{c} is equal to the breakdown voltage of P–N junction $V_{\mathrm{breakdown}}$. Thus, the P–N junction either near the cathode or near the illuminated area will contribute to the leakage current, and in this case no flat region can be seen in the measured I–V curve, as shown by the curves *d* and *e* in Figure 3(a). Assuming the $V_{\mathrm{breakdown}} = V_{\mathrm{cut}} = 1.5$ V, and the $I_{\mathrm{SC}} = 1$ mA, the critical spreading resistance is 1000 Ω. It is useful to estimate the value of shunt resistance and compare it to the sheet resistance of solar cells. Another easy way to discern the cause of the slope is to measure the dark I–V of the device. If the dark I–V is flat near the short circuit region, it is quite possible that the slope in illuminated I–V results from the leakage related to the current spreading.

9. Discussion

Under non-uniform illumination, the leakage of photocurrent is influenced by the lateral voltage distribution. Usually, the junction voltage is large near the light spot, so the leakage starts at this position. Under uniform illumination, there is also lateral voltage distribution. At some spots where the junction voltage is highest, the leakage will emerge very quickly. Therefore there is a critical terminal voltage too. However, in the voltage range corresponding to section S2 and S3, the I–V may not appear to be linear. Because the voltage difference is not very large, once the leakage begins at one spot, the leakage in the vicinity will increase as the terminal voltage rises, and will also result in a large ideal factor for the measured I–V curves. At some extreme cases, the misleading shunt resistance effects will also appear.

10. Conclusion

In summary, the I–V curves of solar cells are investigated from the point of view of leakage of photocurrent. The illumination level-dependent and distribution-dependent I–V curves are well explained. The effective spreading resistance is extracted. The conditions are addressed, under which the widely used one-diode model is improved to understand the dynamic action of I–V curves.

References

[1] Kim W, Choi W. A novel parameter extraction method for the one-diode solar cell model. Solar Energy, 2010, 84: 1008

[2] Ishaque K, Salam Z, Taheri H, et al. A critical evaluation of EA computational methods for photovoltaic cell parameter extraction based on two diode model. Solar Energy, 2011, 85: 1768

[3] Wolf P, Benda V. Identification of PV solar cells and modules parameters by combining statistical and analytical methods. Solar Energy, 2013, 93: 151

[4] Lun S X, Du C J, Yang G H, et al. An explicit approximate I–V characteristic model of a solar cell based on padé approximants. Solar Energy, 2013, 92: 147

[5] Morales-Acevedo A. Lateral current effects on the voltage distribution in the emitter of solar cells under concentrated sunlight. Solar Energy, 2009, 83: 456

[6] Filipi M, Holman Z C, Smole F, et al. Analysis of lateral transport through the inversion layer in amorphous silicon/crystalline silicon heterojunction solar cells. J Appl Phys, 2013, 114: 074504

[7] Xing Yupeng, Han Peide, Fan Yujie, et al. Optimization of the emitter region and the metal grid of a concentrator silicon solar cell. Journals of Semiconductors, 2013, 34: 054005

[8] Jing Liang, Xiao Hongling, Wang Xiaoliang, et al. Enhanced performance of InGaN/GaN multiple quantum well solar cells with patterned sapphire substrate. Journals of Semiconductors, 2013, 34: 124004

[9] Daliento S, Lancellotti L. 3D analysis of the performances degradation caused by series resistance in concentrator solar cells. Solar Energy, 2010, 84: 44

[10] Lai K Y, Lin G J, Lai Y L, et al. Effect of indium fluctuation on the photovoltaic characteristics of InGaN/GaN multiple quantum well solar cells. Appl Phys Lett, 2010, 96: 081103

[11] Huang Y, Dai S, Chen S, et al. Theoretical modeling of the series resistance effect on dye-sensitized solar cell performance. Appl Phys Lett, 2009, 95: 243503

[12] Luque A, Hegedus S. Handbook of photovotaic science and engineering. New York: John Wiley, 2003, Chapter 3

[13] Glatthaar M, Giesecke J, Kasemann M, et al. Spatially resolved determination of the dark saturation current of silicon solar cells from electroluminescence images. J Appl Phys, 2009, 105: 113110

[14] Roth T, Hohl-Ebinger J, Grote D, et al. Illumination-induced errors associated with suns-V_{OC} measurements of silicon solar cells. Rev Sci Instrum, 2009, 80: 033106

[15] Katz E A, Gordon J M, Tassew W, et al. Photovoltaic characterization of concentrator solar cells by localized irradiation. J Appl Phys, 2006, 100: 0440514