

# Operation manual: "Local $I$ - $V$ 2"

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04/2012

## 1. Introduction

This software, which is a further development of the older "Local  $I$ - $V$ " software, is based on the papers "Nondestructive local analysis of current-voltage characteristics of solar cells by lock-in thermography" and "Local efficiency analysis of solar cells based on lock-in thermography" by O. Breitenstein [1, 2]. Its goal is to measure and physically analyze local dark and illuminated current-voltage ( $I$ - $V$ ) characteristics of solar cells according to the two-diode model, based on dark lock-in thermography (DLIT) investigations. Particularly, it allows the user to distinguish between the so-called "diffusion current" density ("first diode" current, being due to recombination in the base and emitter volume and at the surfaces) and the so-called "recombination current" density ("second diode" current, being due to recombination in the depletion region). The software allows one to load a number of DLIT images of a complete cell (maximum four images) taken at different biases  $V_1$ ,  $V_2$ ,  $V_3$ , and  $V_{rev}$ , together with the corresponding data of the biases and flowing current values. From these data it first calculates images of the two-diode parameters  $J_{01}$ ,  $J_{02}$ ,  $n_2$  and the ohmic conductivity  $G_p = 1/R_p$ , based on the different bias-dependencies of the different current contributions. For doing this correctly, the software regards the local series resistance  $R_s$  to different regions of the cell. This  $R_s$ -image can be loaded, e.g. taken from EL- or PL- $R_s$  imaging or from RESI imaging, see [3 - 5]. Alternatively, an image of the local voltage across the p-n junction at the highest forward bias  $V_3$  is loaded and internally converted into an  $R_s$  image according to the RESI principle [5]. This bias image may be obtained also from EL imaging, see e.g. [4] or [6]. Note, however, that the theory underlying this EL procedure does not regard any ohmic or second diode currents. If there are such  $J_{02}$ - or ohmic shunts in the cell investigated, in these regions the voltage obtained from EL evaluation may be erroneous, leading also to erroneous values of  $R_s$ . Alternatively,  $R_s$  may be assumed to be constant across the whole area, which is a good approximation if the investigated cell has no series resistance problems and the current flowing during the DLIT measurements used for this evaluation is not too high.

While the older "Local  $I$ - $V$ " software only calculated dark "suns- $V_{oc}$ " characteristics (i.e. dark characteristics of the local diode, without regarding the series resistance), the new "Local  $I$ - $V$  2" software now also calculates "real" dark and illuminated  $I$ - $V$  characteristics, taking into account the influence of the local series resistance. For doing this, either an image of the short circuit current density  $J_{sc}$  is loaded, or a homogeneous value for  $J_{sc}$  is assumed. This enables the code to calculate, amongst others, realistic images of the local open circuit voltage  $V_{oc}$ , of the local fill factor  $FF$ , the local maximum power point data  $J_{mpp}$  and  $V_{mpp}$ , and of the local efficiency  $\eta$ . Note that these local cell efficiency parameters are only defined for the maximum power point, which, for an inhomogeneous cell, appears in different cell positions at different voltages. Hence, the physical meaning of the local cell parameters  $V_{oc}$ ,  $FF$ ,  $J_{mpp}$ ,  $V_{mpp}$ , and  $\eta$  is the following: These were the parameters of a whole cell having homogeneously the parameters of the considered position. Therefore, these local cell efficiency parameters are actually not allowed to be averaged. Nevertheless, the amount of their local reduction in the position of certain defects allows one to conclude qualitatively how strongly these defects influence certain cell efficiency parameters. Moreover, the

maximum values of the efficiency parameters are a realistic measure of the efficiency potential of a given technology. For performing quantitative investigations, a certain region in a large cell, containing or not containing certain defects, may be selected and considered as one separate cell. Then, by simulating the illuminated characteristic of this region, the efficiency parameters of this cell are calculated, which quantitatively shows the influence of certain defects on the cell efficiency. Another new option is to virtually "cut out" certain local shunt regions. Then, by performing the efficiency analysis of the whole cell, the influence of these shunts is realistically calculated, which can be done also as a function of illumination intensity.

This software may also treat the ideality factor of the second diode  $n_2$  not as a variable but fix it to a value of two, as it is often assumed. In this case the parameter calculation may even be performed analytically. There is also the option to use an ideality factor of the first diode  $n_1$  other than unity. This measure may regard e.g. for an injection level-dependent effective lifetime in the bulk [7]. The dimensions of the DLIT- and  $R_s$ - resp.  $V_3$ -images do not have to be the same, and all images are allowed to be larger than the cell size. In this case the active region may be selected. For each kind of input images bad pixels or extended bad pixel regions may be defined, where the values are filled by averages from the surrounding. This option can also be used for replacing data in busbar regions, which are often shadowed by current leads, by data from their surrounding. For improving the signal-to-noise ratio, quadratic pixel binning is possible. Once the software has calculated the images of the local two-diode parameters  $J_{01}$ ,  $J_{02}$ ,  $n_2$ , and  $G_p$  (which all may be displayed as images,  $J_{01}$  and  $J_{02}$  also in logarithmic scaling), it automatically calculates images of the diffusion current, the recombination current, the ohmic shunt current and the total current densities at all forward biases used. If a  $J_{sc}$  image is loaded or a homogeneous short circuit current density is assumed, images of the local open circuit voltage, the local efficiency, the local "suns" efficiency (without regarding the local series resistance  $R_s$ ), the local fill factor, and the local "suns" pseudo fill factor are calculated, the latter two for the bias ranges  $V_1$ - $V_2$  and  $V_2$ - $V_3$ . Moreover, local dark and illuminated "suns- $V_{oc}$ "  $I$ - $V$  characteristics (without the influence of  $R_s$ ) and "real"  $I$ - $V$  characteristics can be extracted from single points or regions of the cell, up to the whole cell area. For this point or region the cell parameters  $V_{oc}$ ,  $FF$ ,  $pFF$ ,  $\eta$ , suns  $\eta$ ,  $V_{mpp}$ , and  $J_{mpp}$  are calculated. As mentioned above, all these data are simulated under the assumption that each pixel were electrically isolated from the surrounding. Hence, these are actually "efficiency potential" data, which hold for an extended cell having the electrical parameters of the pixel position. In addition, local efficiency parameters (local current density  $J_{loc}$ , local voltage  $V_{loc}$ , efficiency  $\eta$  and fill factor  $FF$ ) for the cell operating at its maximum power point are simulated. All these simulations can be done as a function of the illumination intensity, given in units of "suns".

In the following the basic approximations underlying the "Local  $I$ - $V$  2" software will be summarized:

1. It assumes that the two-diode model and the superposition principle hold. In reality, due to distributed series resistance effects, the series resistance may depend on the current, see next point. There are also other possible departures from the superposition principle [8]. Fortunately, for typical industrial silicon cells their influence is obviously weak [2]. However, thin film solar cells may show strong departures from the superposition principle, therefore "Local  $I$ - $V$  2" is less appropriate for analyzing such cells.
2. It assumes that the series resistance can be described by a local series resistance, based on the local current density and given in units of  $\Omega\text{cm}^2$ . This is a simplification, since it disregards any distributed series resistance effects, which of course may play a role. Therefore, for keeping the voltage drops at the series resistance small and thus

minimizing this error, it is advisable to choose the largest bias  $V_3$  not too high, and to use an  $R_s$  image measured close to  $V_3$ .

3. It assumes that the diffusion current is characterized by a voltage-independent ideality factor  $n_1$  of unity or optionally another fixed value, e.g. due to an injection-dependent lifetime [7].
4. It assumes that the ideality factor of the (depletion region) recombination current  $n_2$  is independent of the bias, which is not always the case. A lower limit of  $n_2$  can and should be set, e.g. 1.5 or 2. If this limit is too close to  $n_1$ , the software cannot distinguish the two contributions from each other anymore.
5. It assumes that the emissivity is homogeneous. In regions with locally reduced emissivity (busbars, grid lines, missing back contact) all currents may be underestimated if the emissivity is not homogenized, e.g. by black color or a sucked-on black plastic foil.
6. It assumes that the heat generated by the series resistance can be neglected. It was shown in [1] that, even if  $R_s$  is large, this simplification still leads to reasonable results. Nevertheless, this also points to the demand on medium currents to be used.
7. It assumes that Peltier effects don't play any role. This is the case if the current in a solar cell flows essentially vertically [12]. For crystalline silicon cells, fortunately the Peltier effect at the grid lines is very weak and usually can be neglected.

## 2. Basics

Dark lock-in thermography (DLIT [9]) images the periodic surface temperature modulation of a device after periodic heat dissipation in the device. It is especially useful for imaging any kind of current flow in solar cells if a pulsed bias is applied in the dark. Assume that the whole cell is imaged and the totally dissipated power is known from the current and the applied voltage ( $P = I \cdot V$ ). Then the LIT signal being  $-90^\circ$  phase shifted to the bias pulses is, within its spatial resolution of about 2 thermal diffusion lengths, a measure of the locally dissipated power density ( $T^{-90^\circ} = \text{local DLIT signal}$ ,  $\langle T^{-90^\circ} \rangle = \text{average value of the DLIT signal over the whole cell}$ ,  $A = \text{cell area}$ ):

$$p(x, y) = \frac{T^{-90^\circ}(x, y) P}{\langle T^{-90^\circ} \rangle A} \quad (1)$$

For thin film solar cells the optimum phase is about  $-45^\circ$  instead of  $-90^\circ$  [9]. The dark current (density)-voltage characteristic of a solar cell is usually described by the two-diode model extended by a series and a parallel resistance  $R_s$  and  $R_p$  (both here given area-related in units of  $\Omega\text{cm}^2$ ,  $V_T = \text{thermal voltage}$ ; 25.57 mV at 25 °C), leading to [9, 10]

$$J(V) = J_{01} \left( \exp \frac{V - R_s J(V)}{n_1 V_T} - 1 \right) + J_{02} \left( \exp \frac{V - R_s J(V)}{n_2 V_T} - 1 \right) + \frac{V - R_s J}{R_p} \quad (2)$$

with 
$$V_{\text{loc}} = V - R_s J(V) \quad (3)$$

being the local voltage across the p-n junction. In (2) the first term is traditionally called "diffusion current" density  $J_{\text{diff}}$  and the second term is called "recombination current" density  $J_{\text{rec}}$ .  $J_{\text{diff}}$  is governed by recombination in the bulk and at the surfaces and  $J_{\text{rec}}$  is due to recombination in the depletion region.  $J_{01}$  and  $J_{02}$  are the saturation current densities of the

diffusion and the recombination current, respectively, being a measure of their magnitudes. The parameter " $n_2$ " is called the ideality factor of the recombination current. If the recombination is caused by point defects,  $n_2$  is lying between 1 and 2, but for recombination via extended defects significantly larger values of  $n_2$  are possible [11]. Therefore also  $n_2$  is an important two-diode parameter. If the minority carrier lifetime is independent of the carrier concentration, the ideality factor of the diffusion current  $n_1$  is always unity. However, if the lifetime increases with increasing current density, it may be slightly larger than unity [7], which can also be assumed in "Local  $I-V$  2". Since  $J_{\text{diff}}$  and  $J_{\text{rec}}$  have different physical origins and influence the efficiency of solar cells in a different way, it is highly desirable to separate these contributions from each other. Though, due to their different bias-dependencies, LIT investigations at low forward bias/current (up to 0.5 V for crystalline Si cells) display preferentially  $J_{\text{rec}}$ -contributions and investigations at high bias/current (at or above 0.6 V) display preferentially  $J_{\text{diff}}$ -contributions, these are always mixed images also containing residues of the other contribution. Therefore, the first goal of the "Local  $I-V$  2" software is to separate  $J_{\text{diff}}$ - and  $J_{\text{rec}}$ -contributions in LIT-based current density images from each other. The second and actually most interesting new goal is to evaluate the influence of the local dark characteristics on the local illuminated characteristics. This provides, for the first time, the possibility to generate realistic images of local cell efficiency parameters open circuit voltage  $V_{\text{oc}}$ , fill factor  $FF$ , and efficiency  $\eta$  for a readily processed solar cell. The possibility to generate dark and illuminated  $I-V$  characteristics of selected points or regions is a powerful tool for understanding the influence of certain local defects on the efficiency.

Within a limited bias range, it is usual to combine the two exponential terms in (2) into one exponential characteristic being characterized by an "effective"  $J_0$  and  $n$ :

$$J(V) = J_0 \exp \frac{V - R_s J(V)}{n V_T} \quad (4)$$

It is well known that images of  $J_0$  and  $n$  may be obtained by performing LIT at two different forward biases  $V_1$  and  $V_2$  and evaluating the results [9]. If the series resistance is neglected ( $V_{\text{loc}} = V$ ), and if the "-1" terms in (2) are neglected (which holds for  $V > 0.5$  V and sufficiently low  $n_2$ ), the power density distribution (1) can be expressed as a current density distribution ( $J = p/V$ ), leading to the following formulas for the ideality factor and  $J_0$ :

$$n = \frac{V_2 - V_1}{V_T \ln \frac{J(V_2)}{J(V_1)}} \quad (5)$$

$$J_0 = \frac{J(V_2)}{\exp \frac{V_2}{n V_T}} \quad (6)$$

The "effective" ideality factor after (5) is also calculated by "Local  $I-V$  2" between  $V_1$  and  $V_2$  and between  $V_2$  and  $V_3$ , respectively. Note that this ideality factor is always bias-dependent, at low forward bias it approximates  $n_2$  (if there is significant recombination current) and at high bias it approximates  $n_1$ . Moreover, this method becomes increasingly inaccurate if a series resistance plays a role, since  $R_s$  tends to increase the effective ideality factor. Fortunately, since  $R_s$  may be compensated in the "Local  $I-V$  2" procedure (see below), the software also calculates images of the "suns- $V_{\text{oc}}$ " effective ideality factor for the two bias ranges.

The "RESI" method [5], which is used in "Local  $I$ - $V$  2" for calculating the local series resistance  $R_s$  from the local bias  $V_3$ , is based on the following principles. For calculating the local value of  $R_s$  we need the local current density  $J$  and the local voltage drop across  $R_s$ , which is  $(V - V_{loc})$ . By EL imaging quite accurate images of the local voltage  $V_{loc}$  may be obtained, leading to the local value of  $(V - V_{loc})$ . DLIT may accurately calculate the local power density  $p$ , see below. From these two values the local value of  $R_s$  is calculated [5].

In the "Local  $I$ - $V$  2" code, LIT measurements at 3 different forward biases  $V_1 < V_2 < V_3$  and one reverse bias  $V_{rev}$  are used to calculate  $J_{01}$ ,  $J_{02}$ ,  $n_2$ , and  $G_p = 1/R_p$  of (2) separately for each image position. Since this problem cannot be solved analytically anymore, an iteration method is used. A unique feature of the "Local  $I$ - $V$  2" code is that it explicitly regards the influence of a local series resistance  $R_s(x,y)$ . This series resistance can either be loaded as an  $R_s$  image  $R_s(x,y)$ . In this image the active area may be selected and its magnitude may be influenced by a scaling factor. Alternatively,  $R_s(x,y)$  may be calculated from an independently loaded  $V_3$ -image according to the RESI principle [5], or a constant value for  $R_s$  can be assumed for all positions. If there is a voltage drop at a series resistance, the local voltage  $V_{loc}(x,y)$  is given by (3). The local power density dissipated by the local diode is in each position  $(x,y)$ :

$$p(x, y) = V_{loc}(x, y)J(x, y) = [V - R_s(x, y)J(x, y)]J(x, y) \quad (7)$$

This can be resolved to:

$$J(x, y) = \frac{V}{2R_s(x, y)} - \sqrt{\frac{V^2}{4R_s(x, y)^2} - \frac{p(x, y)}{R_s(x, y)}} \quad (8)$$

For  $R_s$  approaching zero, (8) reduces to  $J(x,y) = p(x,y)/V$ , as expected. Note that in this treatment the power dissipated at  $R_s$  is neglected by regarding only the power dissipated at the diode. This is a small error as long as the voltage drop at  $R_s$  is small compared to that at the diode (no serious series resistance problem). Even if there is a region of high series resistance in the cell (e.g. a non-contacted region), at least within this region the procedure should work correctly. In this case the main power dissipation at the series resistance should occur at the edge of the high- $R_s$  region where the current flows into this region. Only in this region some errors may be expected. First applications have shown that, even if there are high- $R_s$  regions, the results of the procedure remain reasonable [1].

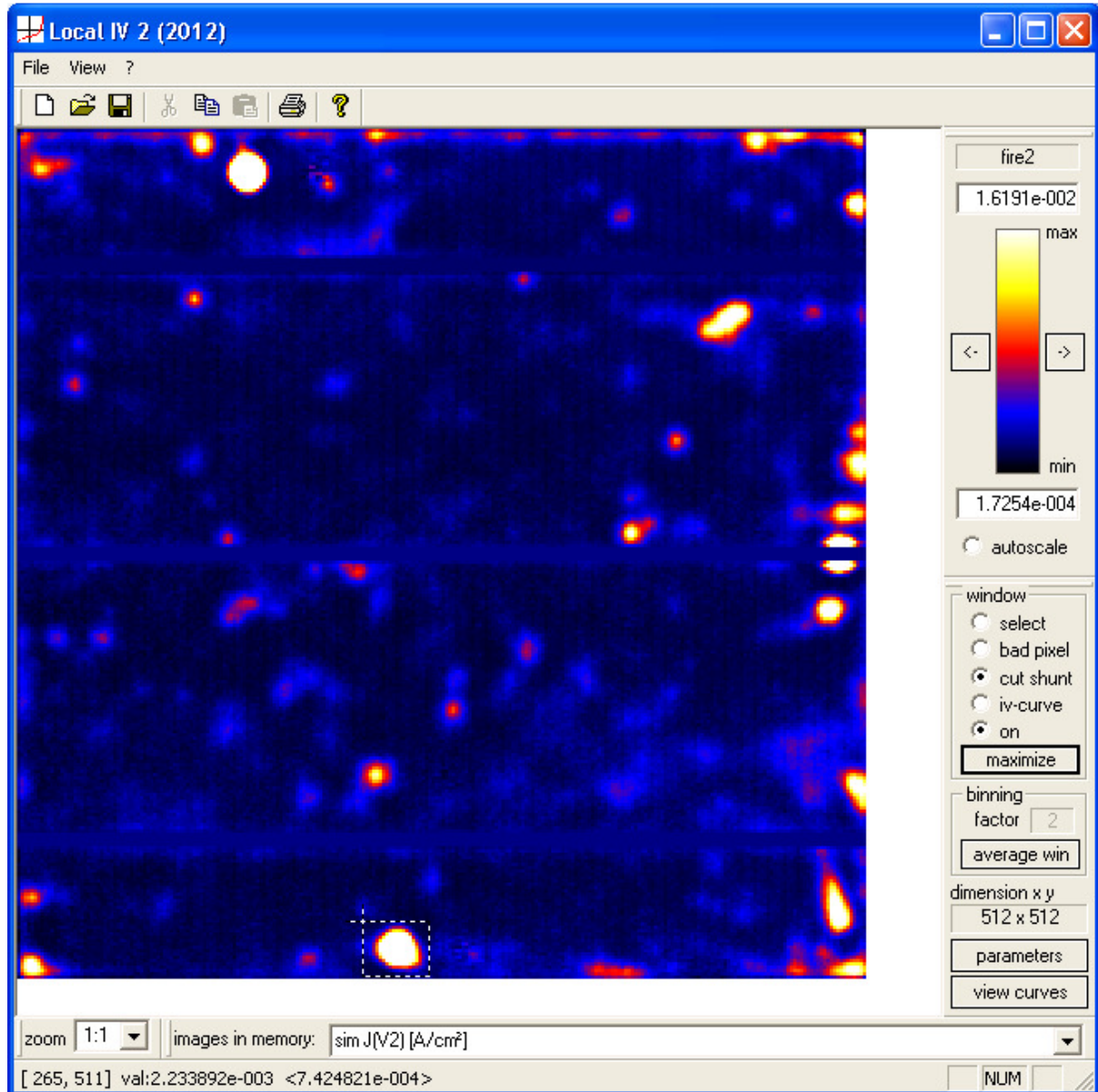
Once the current images for all biases are calculated by (8), the software calculates the local voltages by (3) for all biases and fits the local characteristics at all biases to the two-diode model (2), thereby revealing images of all two diode parameters  $J_{01}$ ,  $J_{02}$ ,  $n_2$  and the ohmic conductivity  $G_p = 1/R_p$  ( $n_1$  is assumed to be constant). Details of this fitting procedure are outlined in [1]. After all two-diode parameters are known, and the  $R_s$  image and a  $J_{sc}$  image are present (or constant  $J_{sc}$  is assumed), the software may calculate numerous other images that are useful for characterizing the cell and its local efficiency, see above and below. Moreover, cell simulations of selected regions and of the whole cell may be performed under various conditions, e.g. for varying illumination intensity.

### 3. Installation

The (eventually packed) installation files contain the executable program file "local\_iv\_2\_2012.exe", one file containing starting parameters "param.ini", this manual, the pdf of [1] and [2], one directory "Pal" containing color palettes, and one directory "Daten" containing two sets of data. If all these files and directories are saved in one working directory, "local\_iv\_2\_2012.exe" should be executable to start the software. At the first

attempt to run this file, the software replies: "register the software by mailing the file KeyA\_loc\_IV\_2.cod to breiten@mpi-halle.mpg.de". Then you will find the new file "KeyA\_loc\_IV\_2.cod" in your working directory, which was generated by the software. After sending this file to breiten@mpi-halle.mpg.de, you will receive a file "KeyB\_loc\_IV\_2.cod", if you are authorized. After this file is copied into your working directory, the software may be used. If your "local\_iv\_2\_2012.exe" file should be replaced by an updated one, you don't need a new "KeyB\_loc\_IV\_2.cod" file. If you want to run this software on another computer, you will need a novel "KeyB\_loc\_IV\_2.cod" file by following the same procedure.

#### 4. Operation



This image shows the main user surface of "Local I-V 2". The "File" menu contains the usual commands for loading or saving different items, printing results, and exiting the software. Note that the "Load Ascii or Bmp" command is not meant for loading any of the input images but rather for loading an extra image (e.g. a luminescence image) which can be displayed for comparison. Special commands in this menu will be explained later on. In the "View" menu at

the top left the visibility of certain display and operation bars can be selected, as a rule they all of them should be checked. Below these menus the "Symbol bar" contains the usual symbols for creating a new project, loading or saving an image, copying an image into the clipboard, or printing the displayed result.

At the bottom left ("Zoom bar") the zoom factor may be selected from 10:1 to 1:10. The "images in memory" menu in the "Image bar" allows the selection of various input and output images. In the "Status bar" below, the cursor position, the image value in cursor position, and the image values averaged across an eventually selected region are displayed. At the top right, the "Scale bar" allows to select the color palette used (default is "fire2") and to scale the image either automatically (autoscale) or manually. Below, the "Settings bar" allows to select different types of windows, the binning factor ("2" means 2x2 binning, to be activated by "average win"), and the dimension of the selected image is displayed. If "select" in "window" is checked, the selection governs the active cell area where the calculations will be made. Such a selection can be done for all input images (the DLIT images  $T_i$  ( $i = 1, 2, 3$ , and rev), and images of  $R_s$ ,  $V_3$ , and  $J_{sc}$ ). Any selection window may be saved and loaded again by the respective commands "Save Selection Window" and "Load Selection Window" in the "File" menu. Depending on the "binning" selection (which acts only for the DLIT images), the selected field in these images can assume only well-defined sizes. The command "maximize" opens all fields to the maximum allowed size. If "bad pixel" is checked, one pixel or a rectangular region in an input image may be selected for bad pixel correction. In this case, right-clicking opens a window containing "set value", "pixel correction", and "cancel". If "pixel correction" is selected, the value of this pixel or this region is replaced by an average of its surrounding pixels, and an internal bad pixel list is updated. If "set value" is selected, the value of this pixel or region may be set, but only in the displayed image. This option does not append the internal bad pixel list. In any of the input LIT images and also in the output images bad pixels may be selected and corrected, the corrections always act on all images. This "bad pixel" option is advantageous also for marking the bus bar regions, where usually both DLIT and luminescence data are meaningless and are thus replaced by meaningful data from the surrounding. The whole bad pixel data list, which is defined for any data type, may be saved and loaded and applied again by respective commands "Load + Run Bad Pixel File" and "Save Bad Pixel File" in the "File" menu. Another option in the "window" field is "cut shunt". This option is intended to virtually cut out shunts in a cell. Also here, the DLIT data in the "cut shunt" region are replaced by mean values of its surrounding. However, in contrast to the "bad pixel" option, here the values of the total current are corrected for each voltage according to the shunt currents in the selected region. After a region is selected in this mode, right-clicking with the mouse opens a window for confirming the cutting procedure. Note that both the "bad pixel" and the "cut shunt" actions are irreversible. If the original situation has to be re-established, the original project has to be re-loaded or the whole project has to be re-defined. If "iv-curve" is checked in the "window" field, the selection governs the pixel or the region where an  $I$ - $V$  curve is calculated, see below. If in this option the button "maximize" is pressed, the  $I$ - $V$  curve refers to the whole cell. Note that, if a whole project is saved, it automatically saves all "select" and all "bad pixel" data under the name given for this project, but not any "cut shunt" data. Hence, the above mentioned options for separate saving single data files are only necessary if the whole work is not saved as a project. The "select" option is only active for all input images ( $T_i$ ,  $V_3$ ,  $R_s$ ,  $J_{sc}$ ), the "bad pixel" option is active for all images, the "cut shunt" option is active for  $T_i$ - and output images, and the option "iv-curve" is only active for calculated output images. Finally, the "Settings bar" contains the two buttons "parameters" and "view curves", which open new windows.

The "parameters" window shown below allows one, in its upper part, to load all input images. Here " $T_1(x,y)$ " is the DLIT image at  $V_1$  and so on.  $V_1$  must be the lowest and  $V_3$  the

highest forward bias. The usual image format are numeric ASCII tables (numbers separated by space or tab, 'enter' at line end), but also bitmap images (\*.bmp) may be loaded. In this case a dialog asks whether the image data shall be interpreted in the range 0 to 1 or 0 to 255. This choice actually does not matter for the evaluation, since the temperature data are anyway converted into current density data by using the entered total currents  $I_i$  ( $i = 1, 2, 3, \text{rev}$ ), see below. For numeric images a dialog asks for the number of header lines to ignore. Note that ASCII images exported by Thermosensorik (now DCG) systems contain one header line. In the same way, images of  $V_3$ ,  $R_s$ , and  $J_{sc}$  may be loaded. The software displays the average values of the images and, for  $V_3$  and  $R_s$ , it allows to set an upper and a lower limit for the data. If the file name of the DLIT images contains the voltage and the current values of the measurement in the form \*xxxmV\* and \*yyymA\* (xxx and yyy being integer numbers), the software automatically recognizes the voltage and bias values and inserts them into the corresponding parameter fields. If this is not the case, these parameters have to be entered there manually. At the bottom of this field a "correction factor  $R_s$ " may be entered, which allows the user to manipulate the  $R_s$  data by multiplying them with this factor. The physical background is that an illuminated series resistance, as measured e.g. by photoluminescence imaging [3], is usually systematically larger than the dark series resistance, which holds for DLIT measurements. Moreover,  $R_s$  images obtained by evaluating EL images [4] still contain a usually unknown factor, which may be corrected here. At the right of this field, other mean values "<Rs>\_scaled" and "<Jsc\_scaled>" are displayed. These values are calculated automatically only at the main calculation procedure. They regard this correction factor and the illumination intensity, and they consider only the data within the selection window of  $R_s$  and  $J_{sc}$ , which were mentioned above.

The screenshot shows a 'parameters' dialog box with the following sections and values:

- load parameters:**
  - T1(x,y) load: V1[V]= 0.497, I1[mA]= 165.000000, <T1> 6.390483e-002
  - T2(x,y) load: V2[V]= 0.546, I2[mA]= 840.000000, <T2> 3.526103e-001
  - T3(x,y) load: V3[V]= 0.597, I3[mA]= 3790.000000, <T3> 1.536757e+000
  - Trev(x,y) load: Vrev[V]= -0.503, Irev[mA]= -7.000000, <Trev> 4.139867e-003
  - V3(x,y) load: min V3= 0.00e+000, max V3= 1.00, <V3> 5.881106e-001
  - Rs(x,y) load: min Rs= 0.10, max Rs= 30.00, <Rs> 9.999988e-001
  - Rs(x,y) from V3(x,y)  constant Rs[Ohm cm<sup>2</sup>]= 0.50, <Rs> loaded 6.540216e-001, scaled
  - correction factor Rs = 1.00
  - Jsc(x,y) load  constant Jsc[mA/cm<sup>2</sup>]= 33.28, <Jsc> scaled 3.328000e+001
- Other parameters:**
  - use n=2
  - neglect Trev
  - Vmax [V]= 1.00
  - intens. [suns]= 1.000
  - area [cm<sup>2</sup>]= 243.00
  - n(Jdiff)= 1.10
  - T amb [°C]= 28.0
  - V T [V]= 2.595e-002
- calculation:**
  - Vmpp,cell [V]= 0.490
  - Voc,cell [V]= 0.604
  - J1(x,y) P1 5.280808e-003
  - J2(x,y) P2 5.352673e-003
  - J3(x,y) P3 6.059014e-003
  - J4(x,y) P4 3.500043e-003
  - Gp(x,y) [S/cm<sup>2</sup>]
  - simulated Images ready
  - LOG(J01(x,y))
  - LOG(J02(x,y))
  - n<sub>eff</sub> [V1-V2]
  - n<sub>eff</sub> [V2-V3]
  - n<sub>2</sub> (x,y) min n<sub>2</sub> 2.00, max n<sub>2</sub> 20.00
  - J01(x,y) min J01[A/cm<sup>2</sup>] 0.00e+000, max J01[A/cm<sup>2</sup>] 5.00e-010
  - J02(x,y) min J02[A/cm<sup>2</sup>] 0.00e+000, max J02[A/cm<sup>2</sup>] 0.10
  - loops: 20
  - min Gp[S/cm<sup>2</sup>] 0.00e+000, max Gp[S/cm<sup>2</sup>] 100.00
- iterative calc:**
  - 
  - 
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In the field below the data input field some options and parameters may be selected resp. entered. If "constant  $R_s[\text{Ohm cm}^2]$ " is checked, the software uses the entered value for all pixels. If "constant  $J_{sc}[\text{mA/cm}^2]$ " is checked, the software uses the entered value for all pixels. If " $R_s(x,y)$  from  $V_3(x,y)$ " is checked, the software internally calculates  $R_s$  from  $V_3$ , as described above. If "use  $n = 2$ " is checked, the software fits the two-diode model assuming  $n_2 = 2$ . In this case only the images taken at  $V_2$  and  $V_3$  are evaluated, hence the image taken at  $V_1$  is not necessary. Note that this approach usually leads to a poorer fit of the characteristics to the measured ones, at least in the low-voltage range. On the other hand, only in this approximation the values of  $J_{02}$  are quantitatively comparable with that of other authors, who are using this approximation. In this field also the assumed ideality factor of the diffusion current " $n(J_{diff})$ ", the illumination intensity "intens [suns]", the cell "area [ $\text{cm}^2$ ]", and the cell temperature " $T^{amb}$  [ $^{\circ}\text{C}$ ]" may be entered, leading to the thermal voltage " $V_T$  [V]". The value " $V_{max}$  [V]" is the maximum voltage up to which the "real" characteristics are internally calculated. This value must be well above the highest value of  $V_{oc}$  of the chosen cell, a default value is 1 V. If this value is chosen too small, unexpected kinks in the simulated characteristics may appear. If there are high- $R_s$  regions in the investigated cell, it may be necessary to choose " $V_{max}$  [V]" even larger than 1 V. Below this field, values of " $V_{mpp,cell}$  [V]" and " $V_{oc,cell}$  [V]" may be entered. These values are necessary for calculating the efficiency parameter images valid for the mpp of this cell. These values may also be submitted from the "IV-curves" window, see below. If the local voltages or currents at the open circuit voltage  $V_{oc}$  shall be calculated, please, insert the value of  $V_{oc}$  in the " $V_{mpp,cell}$  [V]" field and a somewhat higher arbitrary value in the " $V_{oc,cell}$  [V]" field. Then the "sim  $V_{loc}(V_{mpp,cell})$  [V]" and the "sim  $J(V_{mpp,cell})$  [ $\text{mA/cm}^2$ ]" images (see below) will become that at  $V_{oc}$ , but the "sim efficiency( $V_{mpp,cell}$ ) [%]" and "sim FF( $V_{mpp,cell}$ ) [%]" images will become meaningless.

At the lower right side in the "parameters" window some more action buttons are collected. Some of these commands can also be found in the "File" menu. The command to perform the actual DLIT analysis is the button "iterative calc". Alternatively, the button "analytic calc" starts the image evaluation based on an analytic procedure, which is faster than the iterative one. However, this calculation is only possible if  $n_2 = 2$  is assumed, hence starting this calculation automatically checks the "use  $n = 2$ " button. By the calculations described until now, only the so-called "suns- $V_{oc}$ " analysis is performed, and only the output images concerning this analysis (including  $V_{oc}$ ) are automatically generated. Hence, though the local DLIT analysis regards the local series resistance  $R_s$ , the output data are valid for the local diodes and do not consider  $R_s$ . For also calculating "real" characteristics regarding the local  $R_s$ , the "calculate IV" button has to be pressed. This button was separated from the buttons above because the "real"  $I$ - $V$  calculation may consume a few minutes of computation time, depending on the image size and on the computer speed. If only the local dark characteristics of the cell have to be fitted and the "suns" efficiency parameters shall be calculated, it is sufficient to press "iterative calc" or "analytic calc", respectively. Only after the "calculate IV" procedure has been run, images of the "real" efficiency parameters  $V_{mpp}$ ,  $J_{mpp}$ ,  $FF$ , and *efficiency* are calculated, and pressing "IV-curve" displays the  $I$ - $V$  curve of the region or position selected in the main window.

Pressing "load project" or "save project" allows one to load a saved project or to save the current project. This "project" contains all parameter settings including all chosen options, range limits, window and bad pixel data, and the names and locations of all data files. If the software does not find a file in the saved directory, it asks for selecting the directory containing this file. After a project has been loaded, first the "average win" button in the main window has to be pressed for any of the  $T_i$  images, if the project has employed any pixel binning. Then the dark  $I$ - $V$  calculations may be performed by pressing "iterative calc" of

"analytic calc", eventually followed by "calculate IV". The buttons "load params" and "save params" are loading a previously saved parameters set or saving the current parameters set under a chosen name. Here all parameters visible in the "parameters" window are saved, but not the locations of the input files, the "select", and the "bad pixel" data. The commands "suns Voc-curve" and "IV-curves" will be discussed below.

In the "calculation" field some more parameters may be entered. These are min- and max-values for all iteration parameters  $n_2$ ,  $J_{01}$ ,  $J_{02}$ , and  $G_p$  and the number of "loops", which defines how often the iteration loop will be processed (see [1], default is 20). The min- and max-values are provided to prevent that in noisy regions too absurd values are obtained by the iteration procedure, which may falsify mean values of these data. For example, it is advisable to set the lower value of " $n_2$ " to "2" or to "1.5", otherwise the procedure cannot correctly split the current into the two different exponential contributions. If it is observed that in some points or regions the iteration does not fit the measured points correctly, it must be checked whether a too strong limitation of the allowed range for one or more of the diode parameters is responsible for this. Though also negative values are allowed to be entered in "min J01", "min J02", and "Gp", this is physically not meaningful and may lead to difficulties in the internal calculation of the efficiency parameters.

If either the "iterative calc" or "analytic calc" command has been given, after some processing time the output images appear in the "images in memory" menu and the correct calculation of the output images is indicated by checks in the "calculation" field. This action also starts the conversion of "input Jsc" into "scaled Jsc" and the conversion of " $R_s(x,y)$ " or " $V_3(x,y)$ " into "scaled  $R_s$ ", where both the "correction factor  $R_s$ " and the  $R_s$  selection window are regarded. The numbers "P1" through "P4" in the "calculation" field are the proportionality factors between power density and current density for the LIT images T1 through T4. If all measurements have been performed under the same conditions, these 4 values should be lying close together.

As the results of the calculation procedure (triggered by running "iterative calc" or "analytic calc"), the software collects the following output images in "images in memory":

scaled V3 [V]	$V_3$ image with dimensions fitted to the $J$ images
scaled $R_s$ [ $\Omega\text{cm}^2$ ]	$R_s$ image with dimensions fitted to the $J$ images
scaled Jsc [ $\text{mA}/\text{cm}^2$ ]	$J_{sc}$ image regarding "intensity" and fitted to $J$ images
calc J1 [ $\text{A}/\text{cm}^2$ ]	current density at $V_1$
calc J2 [ $\text{A}/\text{cm}^2$ ]	current density at $V_2$
calc J3 [ $\text{A}/\text{cm}^2$ ]	current density at $V_3$
calc -Jrev [ $\text{A}/\text{cm}^2$ ]	current density at $V_{rev}$ (positive values)
calc V1 [V]	local voltage at $V_1$
calc V2 [V]	local voltage at $V_2$
calc V3 [V]	local voltage at $V_3$
calc -Vrev [V]	local voltage at $V_{rev}$ (positive values)
calc Gp [ $\text{S}/\text{cm}^2$ ]	$= 1/R_p(x,y)$ , ohmic parallel (shunt) conductivity
calc $n_2$	ideality factor $n_2$ of $J_{rec}$
calc J01 [ $\text{A}/\text{cm}^2$ ]	saturation current density of $J_{diff}$
calc J02 [ $\text{A}/\text{cm}^2$ ]	saturation current density of $J_{rec}$
calc log(J01)	decadic logarithm of $J_{01}(x,y)$
calc log(J02)	decadic logarithm of $J_{02}(x,y)$
calc neff (V1-V2)	effective ideality factor between $V_1$ and $V_2$
calc neff (V2-V3)	effective ideality factor between $V_2$ and $V_3$
calc neff suns (V1-V2)	effective "suns" ideality factor between $V_1$ and $V_2$
calc neff suns (V2-V3)	effective "suns" ideality factor between $V_2$ and $V_3$

In addition, the software simulates and displays images of all current contributions for the three different forward biases and the "suns- $V_{oc}$ " efficiency-related images:

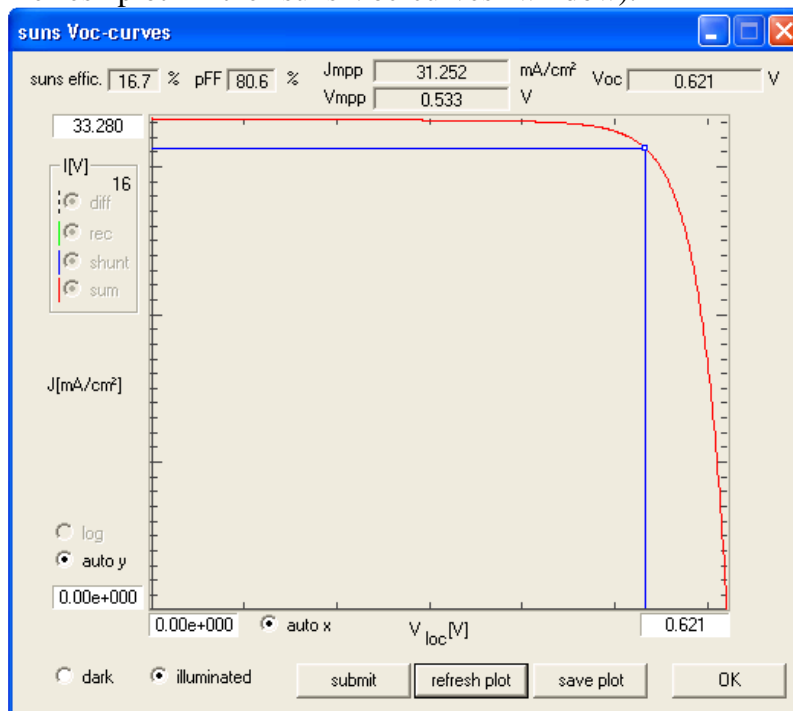
sim Jdiff(V1) [A/cm <sup>2</sup> ]	
sim Jrec(V1) [A/cm <sup>2</sup> ]	
sim Jshunt(V1) [A/cm <sup>2</sup> ]	
sim J(V1) [A/cm <sup>2</sup> ]	
sim Jdiff(V2) [A/cm <sup>2</sup> ]	
sim Jrec(V2) [A/cm <sup>2</sup> ]	
sim Jshunt(V2) [A/cm <sup>2</sup> ]	
sim J(V2) [A/cm <sup>2</sup> ]	
sim Jdiff(V3) [A/cm <sup>2</sup> ]	
sim Jrec(V3) [A/cm <sup>2</sup> ]	
sim Jshunt(V3) [A/cm <sup>2</sup> ]	
sim J(V3) [A/cm <sup>2</sup> ]	
sim suns efficiency [%]	the local efficiency, without the influence of $R_s$
sim Voc [V]	local open circuit voltage
sim suns pFF [%]	local pseudo fill factor, without the influence of $R_s$

After "calculate IV" is pressed, in addition to these images the software simulates and displays the following images:

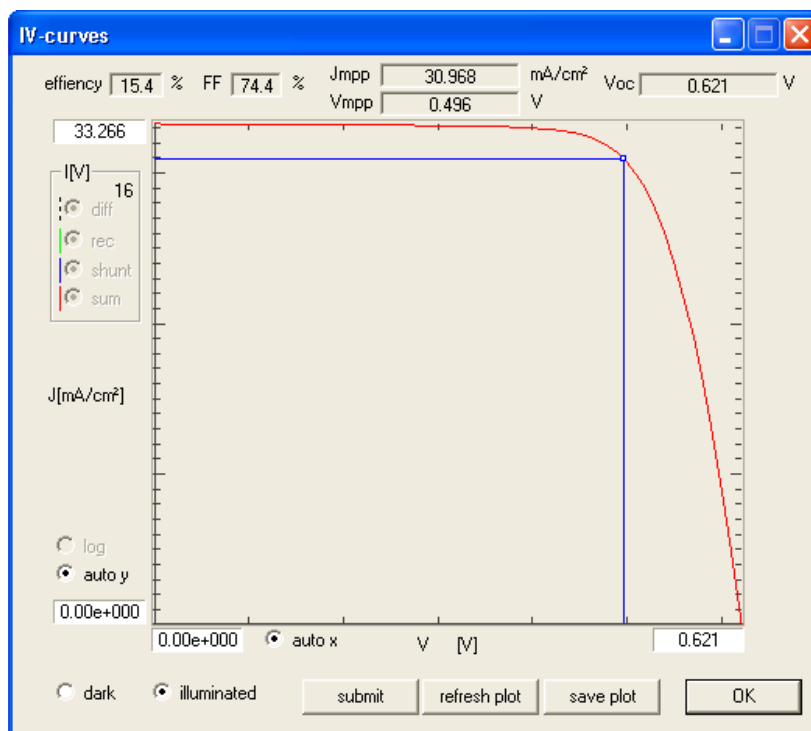
sim efficiency [%]	efficiency, including $R_s$ influence
sim FF [%]	fill factor, including $R_s$ influence
sim Vmpp [V]	maximum power point voltage
sim Jmpp [mA/cm <sup>2</sup> ]	maximum power point current density
sim Vloc(Vmpp,cell) [V]	local voltage, if cell is at $V_{mpp,cell}$
sim J(Vmpp,cell) [mA/cm <sup>2</sup> ]	local current density, if cell is at $V_{mpp,cell}$
sim efficiency(Vmpp,cell) [%]	local efficiency, if cell is at $V_{mpp,cell}$
sim FF(Vmpp,cell) [%]	local fill factor, if cell is at $V_{mpp,cell}$

In all these output images single pixels or certain regions may be selected for calculating  $I$ - $V$  curves of these regions (option "iv-curves" in the "window" field, see above) or for correcting bad pixels or bad pixel regions (option "bad pixel"). After selecting such a region, the average value in this selected region is displayed in the lower left frame of the window as "<[sel:value]>", which enables a simple quantitative evaluation of the image data. Note that this "iv-curves" option is only active for output images, but not for input images. By using the "cut shunt" option, the influence of certain local defects on the efficiency parameters of the whole cell or a region may be corrected. For doing this, in the "cut shunt" mode a certain region has to be selected and then the right mouse button must be clicked. A window appears asking: "cut shunt? Yes / No". After checking "Yes", his measure virtually excludes the defects from cell by replacing their input data by that of their surrounding. Thereby, the total cell current is corrected correspondingly. Then "iterative calc" and "calculate IV" have to be performed again, leading to the efficiency parameters of this whole cell or region without the influence of the excluded defects [2]. Note that the "cut shunt" option is enabled both for input and output images. After selecting a region in one of the input images in this mode, at the bottom left edge the average value across this region appears as "<value1[sel:value2]>". Here "value1" is the average across the active field selected by the "select" option, and "value2" is the average value in the region selected by the "cut shunt" option. This enables a local quantitative data evaluation also in input images.

On the command "suns Voc-curv." in the "parameters" menu or by pressing "view curves" in the main user surface, the code simulates and displays the dark "suns- $V_{oc}$ "-curve of the position or region selected in the main window, including all different current contributions (diffusion, recombination, and shunt currents) separately and the total current according to eq. (2), in the bias range between  $-V_{rev}$  and  $V_3$  in the newly appearing window shown below, together with the data points measured at  $V_{rev}$ ,  $V_1$ ,  $V_2$ , and  $V_3$ . This operation is permitted already before "calculate IV" command was given. If only one point is selected, the curves and the measurement points reflect the fit in this position. If an extended region is selected, the measurement points shown reflect the average current density and the average local bias within the selected region. Note that, even if every pixel in this region should be correctly fitted, in this representation weak voltage differences between the data points and the sum current may appear, since for these non-linear characteristics actually voltage averaging of the measured points, which is performed here, is actually not permitted, if the local voltages are different. Note that these "suns- $V_{oc}$ "-characteristics are characteristics of the local diode, hence they do not consider any series resistance. At the top of the "suns Voc-curves" window the values of the local cell parameters suns efficiency ("suns effic. [%]"), the (suns) pseudo fill factor ("pFF [%]"), and the open circuit voltage ("Voc") of the selected pixel or region are displayed. Moreover, the maximum power point data "Jmpp" and "Vmpp" are indicated. By checking the option "illuminated" at the bottom left, the illuminated characteristic is displayed. Here only the sum characteristic is displayed, but the position of the maximum power point is marked. The x- and y-scaling of the dark plot can be set manually or automatically, in the "I[V]" field it can be selected which curves are displayed, and the display of the dark characteristic can be performed linearly or semi-logarithmically. By pressing "save plot", all iv-curves (the dark and the illuminated one), the measured dark current data (including the  $R_s$ -corrected voltage), and the local cell parameters can be saved as an ASCII table. Pressing "OK" closes the "suns Voc-curves" window, just as for the "parameters" window. If "refresh plot" is checked, the plot is refreshed to an eventually newly selected region. If the main user surface is the currently active window and a point or region is selected in the "iv-curve" mode there, the cursor keys allow to shift the selected region, and pressing the "ENTER" key always updates the displayed  $I$ - $V$  characteristics (equivalent to "refresh plot" in the "suns Voc-curves" window).



By pressing "IV-curves" in the "parameters" window, the "real"  $I$ - $V$  curve, shown below, of the position or region selected in the main window, including the influence of  $R_s$ , is displayed. This works only if before "calculate IV" was performed, otherwise an error message appears. All display options described above for the "suns Voc-curves" also hold for the "IV-curves, except of the separate imaging of the different dark current contributions. This separate imaging is not possible here since  $R_s$  only acts on the total current and not on its constituents. The fill factor (FF) and the efficiency displayed at the top are now the realistic values for the selected region, based on the approximations mentioned in the Introduction. If in the "IV-curves" window the data are saved by pressing "save plot", the realistic dark and illuminated  $I$ - $V$  data between 0 V and "Vmax [V]", given in the "parameters" window, are saved, together with the current- and voltage data of the DLIT measurements. Note that, if an  $I$ - $V$  curve is displayed, and any parameter is changed or some shunts are cut out, after pressing "iterative calc" the software automatically performs also "calculate IV", recalculates the characteristic, and displays the efficiency parameters. Note that, if the whole cell area is selected in the main window, the parameters displayed in the "IV-curves" window are the efficiency parameters simulated for the whole cell. The "submit" button allows one to automatically submit the  $V_{mpp}$  and  $V_{oc}$  data to the respective data fields in the "parameters" window, where they are used for simulating the local efficiency data for the case that the cell is at its own mpp.



### Feedback, warranty

Please, report any bugs or proposals for improvements of this software and its description to Otwin Breitenstein (breiten@mpi-halle.mpg.de). Within 2 years after purchasing this software, possible bugs will be removed free of charge.

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