

Description Electroluminescence (EL) Imaging Evaluation Software

"EL-Fit"

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Introduction

This software is based on the papers "Quantitative evaluation of electroluminescence images of solar cells" by O. Breitenstein, A. Khanna, Y. Augarten, J. Bauer, J.-M. Wagner, and K. Iwig [1] and "Evaluation of luminescence images of solar cells for injection-level dependent lifetimes" by S. Rißland and O. Breitenstein [2]. It allows one to load a number of electroluminescence (EL) images to different biases, which have to be given as ASCII tables. By using an iterative procedure, from two of the EL images the software allows one to calculate an image of the local area-related series resistance R_s (in units of Ωcm^2) and of the local saturation current density of the diffusion current density J_0 (in units of A/cm^2). For regarding a possible carrier concentration-dependent lifetime, the ideality factor of the diffusion current may be chosen to differ from unity. This procedure is based on the Fuyuki approximation [3] saying that the luminescence intensity is proportional and the dark saturation current density is inversely proportional to an "effective diffusion length" in the base, which also takes into account a finite base thickness and backside recombination. Due to its iterative nature, the procedure works correctly even if both EL measurements are made at a relatively high voltage resp. current, which enables low acquisition times. From the J_0 -image the software also calculates images of the effective lifetime and the effective diffusion length in the base for the two selected EL voltages (since the lifetime may be injection-dependent), and the local open circuit voltage potential. The generally unknown proportionality factor "f" may be fitted so that either the average series resistance, the average saturation current density, or the open circuit voltage of the cell matches the value taken from the dark or illuminated I-V characteristic of the whole cell. Moreover, from one selected EL image (taken at a possibly low voltage) an "ohmic shunt" image of the ohmic parallel conductance G (given in units of S/cm^2) may be derived. This procedure is based on the approximation of an otherwise homogeneous cell, hence here the series resistance and also the bulk lifetime are assumed to be homogeneous. It can only be applied to sufficiently strong ohmic shunts. Especially for multicrystalline cells, the resulting shunt image is not as exact as lock-in thermography results due to the coarse approximation of a homogeneous lifetime used here. The software also calculates the local bias images (considering the voltage drop at the local

series resistance) for both evaluated EL images. If the first EL image used was taken at such a low bias that voltage drops at the series resistance is negligible, the resulting $V_{2,loc}$ image is not influenced by the Fuyuki approximation. Hence, it is expected to be quite realistic, except for positions influenced by ohmic or depletion region recombination-induced shunts, which are not included in the "EL-Fit" procedure. This bias image can be used for calculating an R_s image in the "Local $I-V$ 2" lock-in thermography evaluation software in analogy to the "RESI" technique described in [4]. This image is more realistic than the R_s image calculated by "EL-Fit" itself, since it does not depend on the unknown factor "f" and does not rely on the Fuyuki approximation but uses the local current density values measured by DLIT. It is also more realistic than a photoluminescence-based R_s image, since the latter represents the "bright" (illuminated) series resistance, whereas for EL and DLIT the "dark" series resistance is decisive. These two data sets usually differ from each other [5]. The "Local $I-V$ 2" software is also available from Max-Planck-Innovation GmbH, Munich [6].

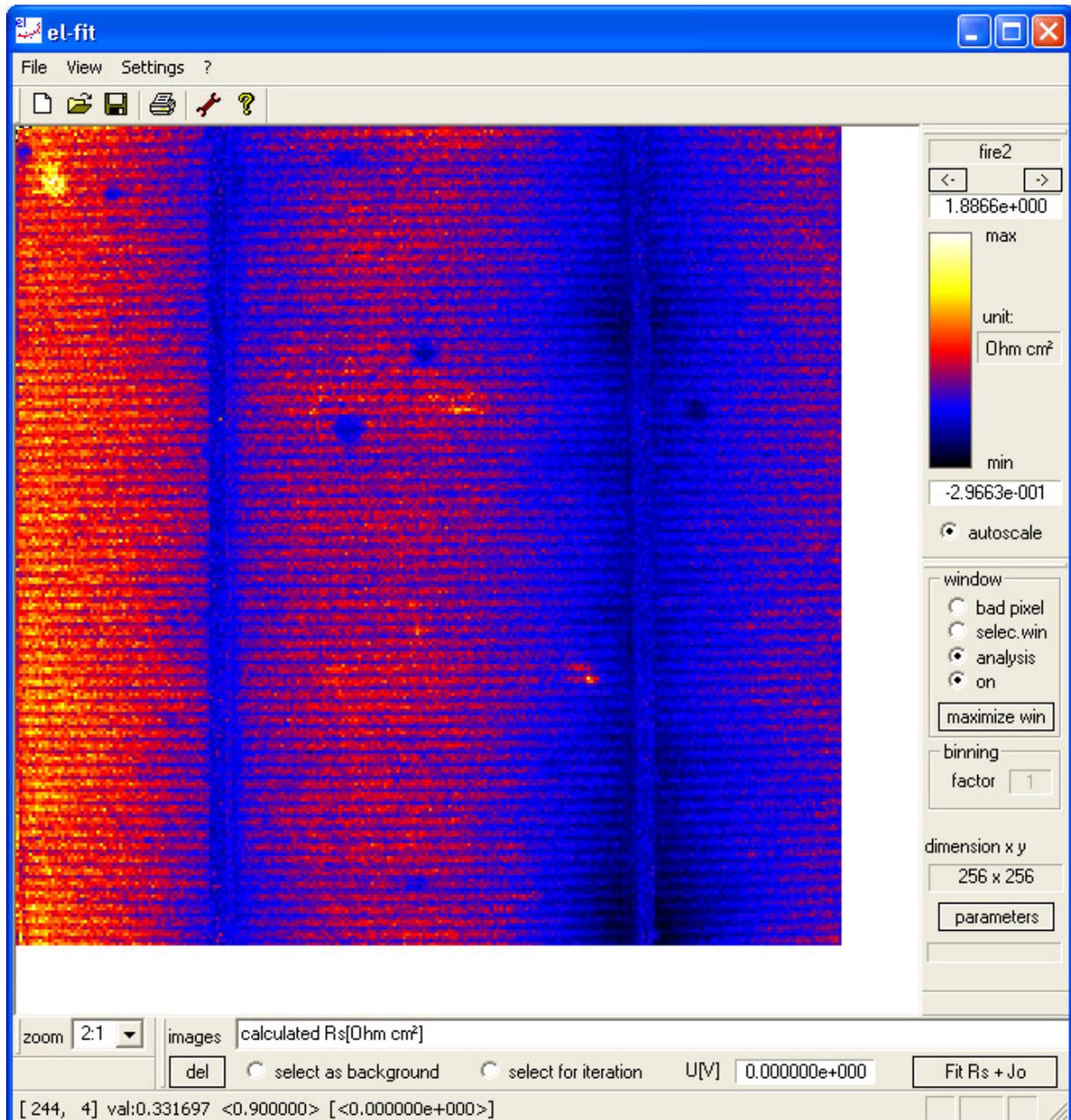
Installation

The (eventually) packed installation file contains the executable program file "el-fit.exe", one file containing starting values "startval.ini", this manual, one directory "Pal" containing color palettes, one directory "elfitdaten" containing typical EL data, and the pdf of ref. [1, 2]. If all these files and directories are saved in one working directory, "el-fit.exe" should be executable to start the software. At the first attempt to load an image, the software replies: "register the software by mailing the file KeyA_el_fit.cod to breiten@mpi-halle.mpg.de". Then you will find the new file "KeyA_el_fit.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_el_fit.cod", if you are authorized. After this file is copied into your working directory, the software may be used. If your "el-fit.exe" file should be replaced by an updated one, you don't need a new key file. If you want to run this software on another computer, you will need a novel "KeyB_el_fit.cod" file for this computer by following the same procedure.

Operation

The image below shows the main user surface of "EL-Fit". An arbitrary number of EL images can be loaded into the image pool of EL-Fit by selecting "File => load image" at the top left of the user surface shown below. For each image the number of headlines to be ignored can be selected and the data format can be checked. Image loading has to be stopped by selecting

"cancel" or the "Close"-cross at the top right of the loading window. These images will become available in the "images" selection field at the bottom. Any EL image can be removed from the image pool by pressing the "del" button at the lower left, if this image is displayed. If the "autoscale" option at the right is activated, all displayed images are independently scaled to their individual minimum and maximum values. Alternatively, scaling limits may be inserted manually into the fields above and below the scaling bar. These manual scaling limits will remain if another image is displayed.



By pressing the horizontal arrows at the top right (-> and <-), different color palettes may be selected; the names of the palettes appear at the field above. We suggest to use the "fire2" or the "hot metal" palette since they can intuitively be interpreted and are still meaningful as a

grey copy. If the names of the EL images contain the character line "...XYZmV..." (XYZ being a 3-digit number), the software automatically recognizes the voltage belonging to the image as "XYZ mV" and displays it in the field "U[V]" below the "images" selection field. If this automatic voltage recognition procedure should not work, the voltages of all images have to be inserted manually into the "U[V]" field, if the corresponding image is displayed, otherwise the software cannot work correctly. As a rule, the data value "0" of the ASCII images does not belong to zero detected photons, and any camera has an inhomogeneous dark signal. Therefore, for enabling quantitative evaluations, an additional "background" EL image has to be taken under the same conditions as for the EL images, but without powering the cell. Also this background image has to be loaded into the image pool. If this image is displayed, by checking "select as background", this image is automatically subtracted from all other EL images. If the input images are already baseline-corrected, this "background" image is not necessary.

In the "zoom" selection at the bottom left the display zoom factor for all displayed images can be selected. Often original EL images are of very high resolution (1024x1024 or 2048x2048 pixel) and show an area larger than the actual cell size. Therefore EL-Fit implies pixel binning and area selection. Pixel binning degrades the spatial resolution but improves the signal-to-noise ratio of the results. The single number inserted in the field "binning" at the right (between 1 and 10) defines the pixel binning, hence "4" means "4x4 pixel binning", which improves the signal-to-noise ratio by a factor of four. If "selection win" at the right is checked, the user may draw a selection field into any of the original EL images. All evaluations will be made only in the selected field by using the selected pixel binning. In the region outside of the selected field all output values are set to zero. Pressing the "maximize window" button at the right maximizes the window. If pixel binning larger than "1" is selected, it is possible that this maximum window leaves an unused edge at the right and the bottom, since this window is defined regarding the pixel binning. The selection window may be saved by "File => Save Selection Window", and a formerly saved window may be loaded by "File => Load Selection Window". If the "bad pixel corr" button in the "window" field at the right is checked, the user may click on an eventual bad pixel or may choose an extended bad region (e.g. a bus bar) in an EL image. Then, after right-key clicking anywhere, a window containing "set value / pixel correction / cancel" appears. If here "pixel correction" is selected, in all images the value of this pixel or region is replaced by the median of all surrounding pixels. The "median" is an average that does not consider strongly outrunning values. Note that these pixels have to be within the region of the "select" window. If bad pixels outside of

this regions have to be corrected (e.g. for ensuring that the "autoscale" function is running correctly), the "select" region has to be maximized before. After a number of bad pixels are marked, this bad pixel information can be saved under "File => Save Bad Pixel File". If results of the same camera are used again, this bad pixel file can be used again by selecting "File => Load + Run Bad Pixel File". Generally, for all displayed images the pixel values in cursor position are displayed together with the pixel position at the bottom left. If in the "window" field "analysis" is checked and a region is selected in any image, the average value in this region is displayed there as <average>. All displayed images can be saved as ASCII tables by selecting "File => Save ASCII-Image", saved as bitmap files by selecting "File => Save BMP-Image", or printed out by selecting "File => Print". A project can be saved under a given name by selecting "File => Save Project" and loaded again by pressing "File => Load Project". By this measure all used file locations and parameters together with the window and bad pixel data are saved. A new project can be started by selecting "File => New Project" or the corresponding symbol at the top right, where also symbols for file loading, saving, and printing are available.

The screenshot shows a software window titled "parameters" with a close button (X) in the top right corner. The window contains several input fields and buttons for configuring parameters. A "set to default" button is located in the top right of the parameter list.

| Parameter | Value | Unit | Description |
|-------------------|----------------|----------------------|---------------------------------|
| n_1 | 1.000000 | | ideality factor |
| U_T | 0.025692 | V | thermal voltage |
| T | 25.000000 | °C | |
| n_i | 1.380000e+010 | cm ⁻³ | intrinsic carrier concentration |
| μ | 1000.000000 | cm ² /V·s | minority carrier mobility |
| N_A | 1.000000e+016 | cm ⁻³ | doping level |
| J_{sc} | 31.000000 | mA/cm ² | short circuit current density |
| f | 5.466525e-020 | A/cm ² | |
| global R_s | 9.000000e-001 | Ohm cm ² | |
| global J_0 | 9.600000e-013 | A/cm ² | |
| measured Voc | 0.640000 | V | |
| < R_s > | 9.001595e-001 | Ohm cm ² | fit f to global R_s |
| < J_0 > | 4.582928e-013 | A/cm ² | fit f to global J_0 |
| cell <Voc> | 8.181552e-001 | V | fit f to meas Voc |
| R_s min | -3.000000e-001 | Ohm cm ² | |
| J_0 max | 1.500000e-011 | A/cm ² | |
| No. of iterations | 20 | | |

Buttons: "set to default", "cancel", "OK".

Before calculating images of the series resistance R_s and the saturation current density J_0 , two of the loaded EL images have to be selected for iteration. This can be done by checking "select for iteration" at the bottom, if these images are displayed. The parameters used for the calculations can be selected in the "parameters" window (shown above), which is available by pressing the "parameters" button at the bottom right of the user surface or under "Settings". Here the temperature "T" can be selected in °C (default value is 25 °C), the corresponding thermal voltage " V_T " is displayed, and values for the intrinsic carrier concentration, the minority carrier mobility, and the base doping concentration may be defined. These parameters are used for calculating the images of the effective bulk lifetime and the effective bulk diffusion length, which are automatically calculated together with the image of the saturation current density J_0 by using the well-known formulas for infinitely thick solar cells. Since all solar cells have a limited thickness and the bottom surface recombination velocity contributes to the bulk lifetime, these are "effective" values. Moreover, here the ideality factor " n_1 " of the "first diode" current may be inserted. The default value is unity, but if the lifetime is injection-level dependent, it may be larger than unity [7]. Finally, here the short circuit current density " J_{sc} [mA/cm²]" may be selected, which is used for calculating the image of the bulk-limited open circuit voltage " V_{oc} [V]" and the expected V_{oc} of the whole cell. Note that these data do not contain the influence of the emitter on J_{01} , hence these values, as well as the additionally displayed value of "cell V_{oc} " will usually be larger than the measured values. In the field below the proportionality factor "f" according to [1] has to be set (typical value 10^{-19} A/cm²), and the "No. of iterations" has to be selected at the bottom. As a rule, convergence better than 0.1 % (as visible e.g. by the values of the average series resistance $\langle R_s \rangle$ and saturation current density $\langle J_0 \rangle$ shown in the "parameters" window after a calculation) is achieved already after 5 - 10 iterations, with 20 iterations you are always on the safe side. For a new sample, this factor "f" is generally unknown, so the first calculation has to be done with an arbitrary value of "f". The calculation is started by pressing "Fit $R_s + J_0$ " after closing the "parameters" window. This procedure generates the "calculated R_s [Ohm cm²]" and "calculated J_0 [A/cm²]" images, the first one being shown automatically after the calculation. Moreover, this action produces images of "calculated R_s (Ohm cm²) cut" and "calculated J_0 [A/cm²] cut", explanation for both see below, and images of "calculated $U_{loc,1}$ [V]", "calculated $U_{loc,2}$ [V]", "eff. lifetime (1) [s]", "eff. lifetime (2) [s]", "eff. diffusion length (1) [cm]", and "eff. diffusion length (2) [cm]". The two values of the effective lifetime and diffusion length belong to a possible injection-level dependent lifetime, which is expressed here as an ideality factor Note that these data are strongly dependent on the chosen material

parameters, especially on n_i , which is strongly temperature-dependent. The default value of $1.38 \cdot 10^{-10} \text{ cm}^{-3}$ refers to 25 °C.

Then the factor "f" may be adjusted after the first calculation either so that the global value of R_s , taken e.g. from the evaluation of the dark I-V characteristic, matches the average value of the R_s -image, or that the global J_0 taken from the I-V characteristic matches the average of the J_0 -image, or that the measured open circuit voltage of the cell matches the simulated one. These global values can be inserted in the "parameters" window under "global R_s [Ohm cm^2]", "global J_0 [A/ cm^2]", or "measured V_{oc} [V]". After a first calculation has been made, the "parameters" window displays the average values $\langle R_s \rangle$ and $\langle J_0 \rangle$ of the two images, as well as the simulated "cell $\langle V_{oc} \rangle$ ". If then either the "fit f to global R_s ", the "fit f to global J_0 ", or the "fit f to meas V_{oc} " button is pressed in the "parameters" window, the factor "f" changes. If then the "parameters" window is closed and a new calculation is made by pressing "Fit $R_s + J_0$ " again, the average value of R_s or J_0 or the simulated V_{oc} , respectively, of the newly appearing results should match the global resp. measured values. On demand, this procedure may be repeated. Note that the appearing series resistance R_s is the "dark R_s " which is significantly lower than the "illuminated (light) R_s ", which is obtained e.g. by comparing dark and illuminated I-V characteristics or evaluating photoluminescence images [5]. Note also that, in the regions of bus bars, finger grids, and outside the cell, this evaluation reveals meaningless values for R_s and J_0 . In fact, in these regions the local values of R_s appear generally too low and that of J_0 too large. Therefore the "parameters" window contains an option to "cut" for all R_s values below and all J_0 values above a certain value. The operator has to find these values by manually scaling the uncut "calculated R_s (Ohm cm^2)" and "calculated J_0 (A/ cm^2)" images meaningfully and insert the corresponding " R_s min" and " J_0 max" values in the "parameters" window. In addition to the "calculated R_s (Ohm cm^2)" and "calculated J_0 (A/ cm^2)" images, the software always produces also "calculated J_0 [A/ cm^2] cut" and a "calculated R_s (Ohm cm^2) cut" images according to these selected limits. The advantage of this procedure is that the average values of $\langle R_s \rangle$ and of $\langle J_0 \rangle$ are calculated from the "cut" values. Especially for J_0 this is more meaningful than using the uncut values, since the cut values are not disturbed so strongly by the meaningless values in the bus bar regions. The effect of the cutting procedure can be checked within the "parameters" window by changing the cutting limits " R_s min" or " J_0 max". Then the displayed values of $\langle R_s \rangle$ and $\langle J_0 \rangle$ change correspondingly. Also by defining the bus bar regions as "bad pixel" regions, the average values of R_s and J_0 can be made more realistic.

The conversion of EL images into shunt images of the parallel conductivity "Gp" is based on the assumption of relatively strong ohmic shunts and the approximation that the series resistance and saturation current density distribution resp. the lifetime is homogeneous [1]. Since these approximations are very coarse, even for ohmic shunts the result is only approximate. Since EL cannot distinguish between linear (ohmic) and non-linear (diode-like) shunts, and since the procedure implemented becomes inaccurate for weak ohmic shunts, this software cannot replace the lock-in thermography technique. For calculating the shunt image you have to display one EL image, which should be taken at a possibly low bias for keeping the systematic error due to the series resistance in the area small [1]. By pressing the "Generate Gp" button the shown EL image is converted to an image called "calculated Gp [S/cm²]", which is immediately displayed. For multicrystalline cells the residual grain structure in this image is a systematic error due to the assumed homogeneity of the lifetime.

Feedback and 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.

References:

- [1]: O. Breitenstein, A. Khanna, Y. Augarten, J. Bauer, J.-M. Wagner, and K. Iwig: "Quantitative evaluation of electroluminescence images of solar cells", Phys. Stat. Sol. RRL **4**, 7-9 (2010)
- [2] S. Rißland, O. Breitenstein: "Evaluation of luminescence images of solar cells for injection-level dependent lifetimes", in preparation.
- [3]: T. Fuyuki, H. Kondo, A. Ogane, Y. Takahashi: "Analytic findings in the electroluminescence characterization of crystalline silicon solar cells", J. Appl. Phys. **101**, 023711 (2007)
- [4]: K. Ramspeck, K. Bothe, D. Hinken, B. Fischer, J. Schmidt, R. Brendel, "Recombination current and series resistance imaging of solar cells by combined luminescence and lock-in thermography", Appl. Phys. Lett. **90** (2007) 153502.
- [5]: A.G. Aberle, S.R. Wenham, M.A. Green: A new method for accurate measurements of the lumped series resistance of solar cells", Proc. 22th IEEE PVSC Louisville (2002), pp. 133-139
- [6] <http://max-planck-innovation.de/en/>

- [7] D. Macdonald, A. Cuevas, "Reduced fill factors in multicrystalline silicon solar cells due to injection-level dependent bulk recombination lifetimes", *Prog. Photovolt: Res. Appl.* **8** (2000) 363-375.