SOLAR EYE

SOFTWARE MANUAL

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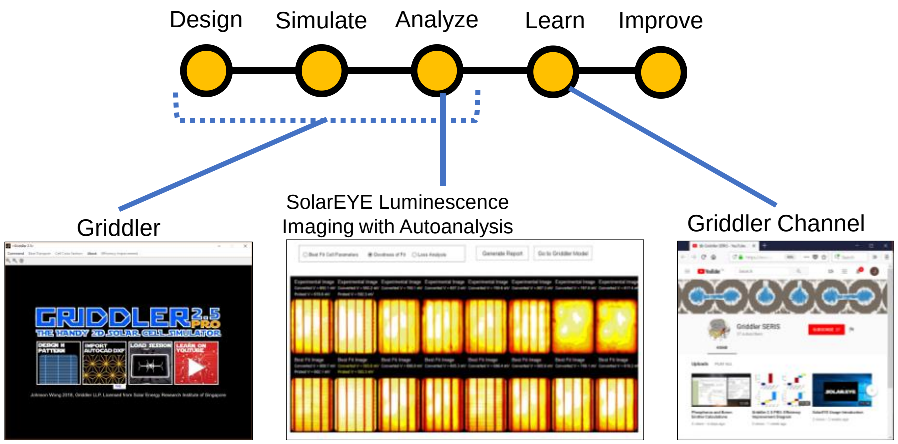
1.1 Introduction

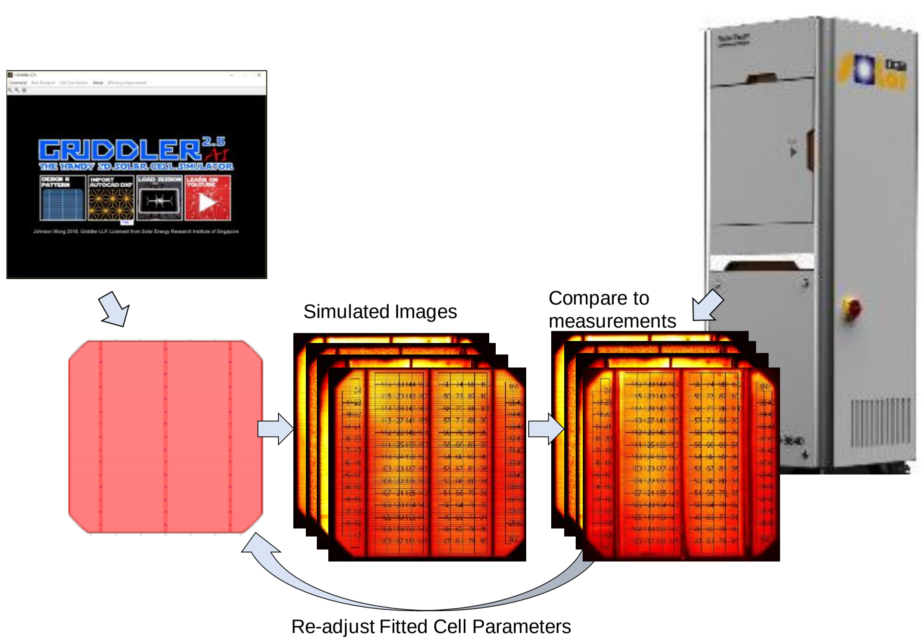
SolarEYE is an integrated luminescence imaging hardware + software analysis platform that automates the workflow of luminescence imaging + Griddler AI autofitting and cell parameters extraction + Griddler model building + loss analysis. This manual will cover the software aspects.

SolarEYE was created at the Solar Energy Research Institute of Singapore (SERIS) in 2017. It is an automation of many important steps in the analysis of silicon solar cells and related samples, and forms an important backbone in the development cycle of solar cells employed at SERIS, which can be represented by the chain below:

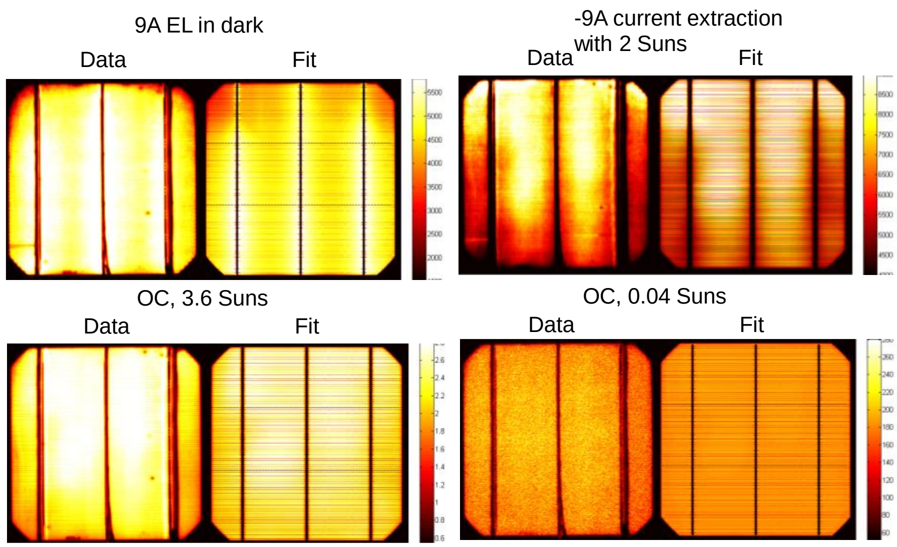


1.2 SOLAREYE Core Model

SolarEYE combines Griddler, a finite-element simulator for solar cells (see Griddler manual), and tailored multivariate regression techniques, in a general computational routine which seeks cell parameters that can best explain a set of luminescence imaging data. Below we show the generic computational process flow that leads to the cell parameters of best fit.

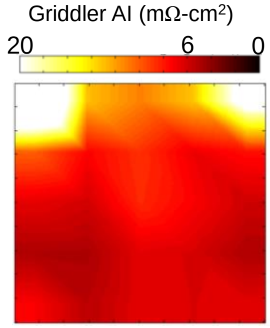


Below we show the set of luminescence images for a solar cell and the corresponding best fit simulated luminescence images from SolarEYE.



The auto fitting procedure allows detailed cell parameters to be extracted, so that the user can separate out the different factors limiting a solar cell's efficiency. For instance, the fit above enables SolarEYE to delineate the spatial distribution of a cell's front metal grid contact resistance, shown below to the left. This map is compared to contact resistance values measured by the much slower and destructive TLM method, as well as to the emitter sheet resistance. Agreement is decent though SolarEYE predicts a higher contact resistance. There is also good correlation between SolarEYE's extracted contact resistance and the emitter sheet resistance, which is within reasonable expectations.

Contact resistance by Griddler AI (mΩ-cm^2)



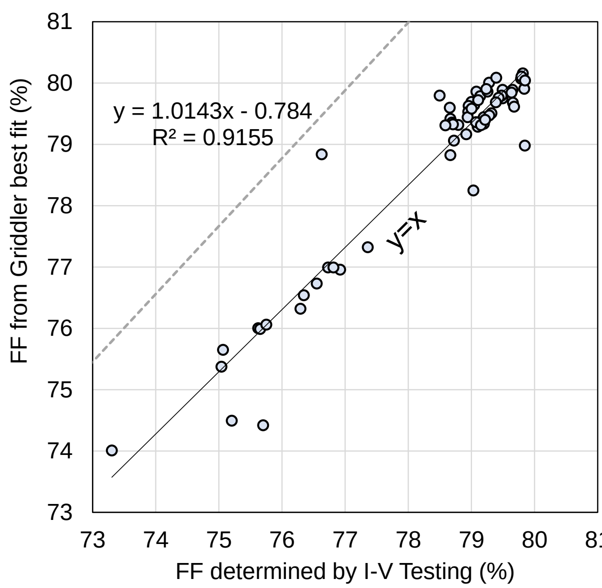
Contact resistance by TLM (mΩ-cm^2)

5.7	4.0	5.4	14.4
4.9	3.8	3.8	9.2
4.1	3.5	3.2	5.3
5.1	4.0	4.4	4.2

Emitter sheet resistance by TLM (Ω/sq)

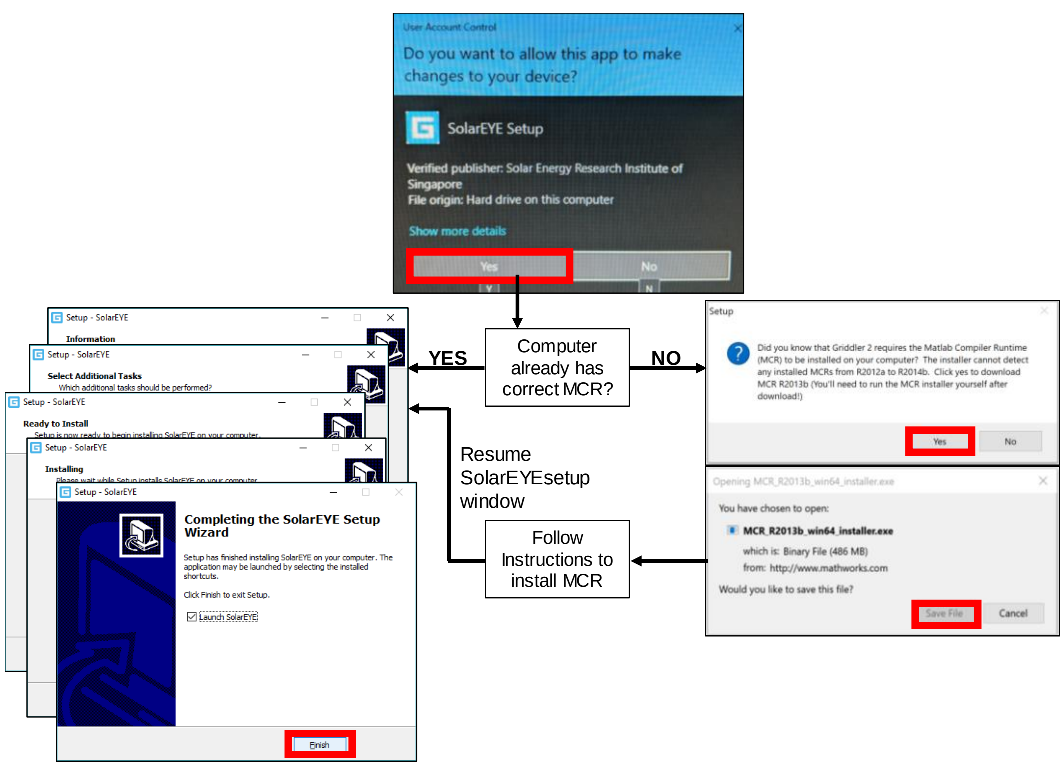
88.5	81.0	84.1	93.5
78.9	77.9	79.0	86.6
76.5	76.4	77.2	80.0
75.5	75.1	75.1	76.9

In a 2017 study (J. Wong, P. Teena, D. Inns, "Griddler AI: New Paradigm in Luminescence Image Analysis Using Automated Finite Element Methods", 44th IEEE PVSC, Washington (2017)), 80 solar cells that went through the SolarEYE autofitting procedure, led to best fit cell parameters in contact resistance and recombination currents that, when input into Griddler, yielded simulated I-V curve fill factors that agreed with experimental data:

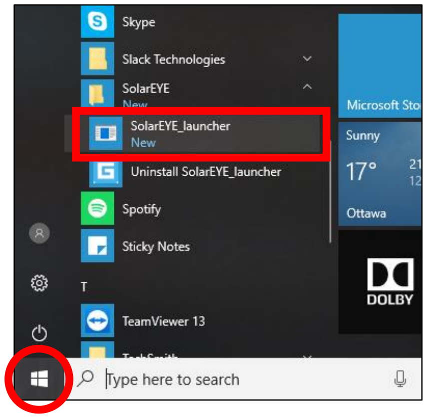


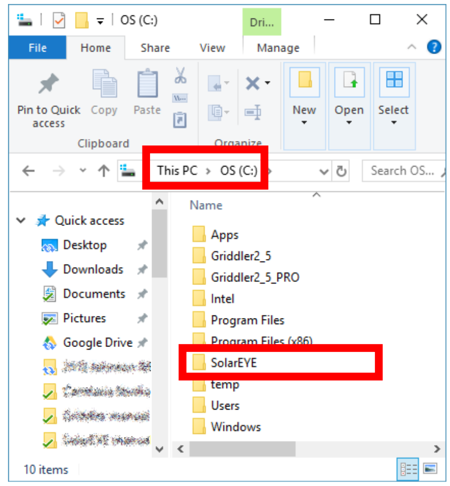
2.1 Installation and First time Use

SolarEYE comes preinstalled with the luminescence imaging tool, but for updates, you can download SolarEYE installers for 64 bit windows computers. The installation process is automatic and easy to follow and is described by the diagram below. SolarEYE is written in MATLAB and requires the Matlab compiler runtime (MCR R2013b) to run. The installer will autodetect the presence of the correct MCR version and download it if it is missing.



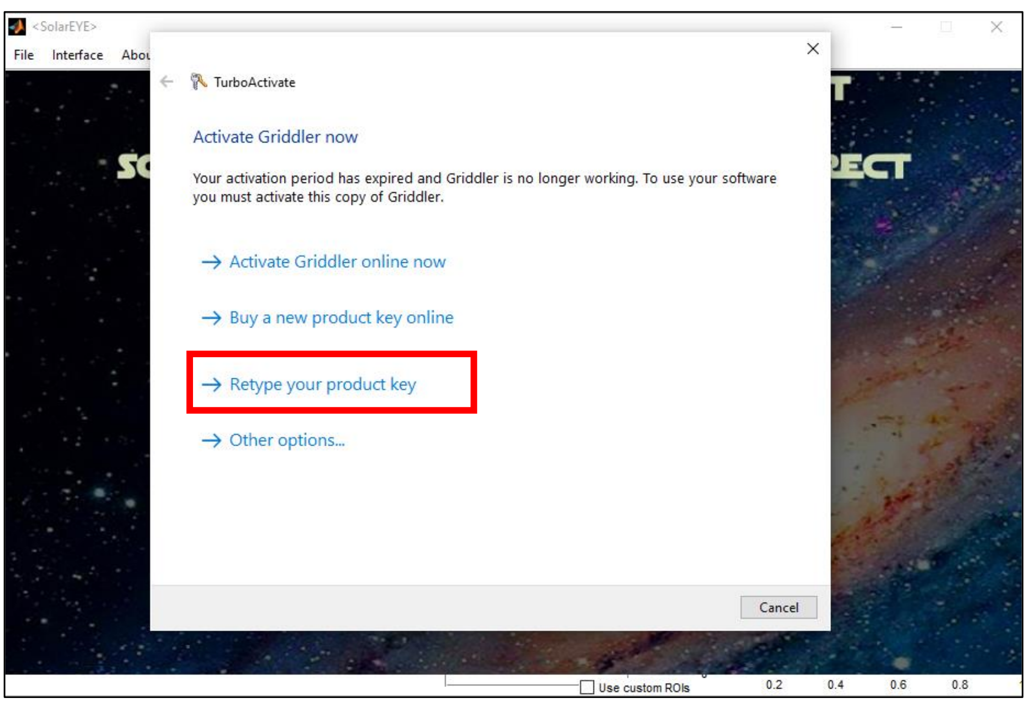
By default, you should be able to launch SolarEYE either from the start menu (below), or from C:\SolarEYE\SolarEYE.exe





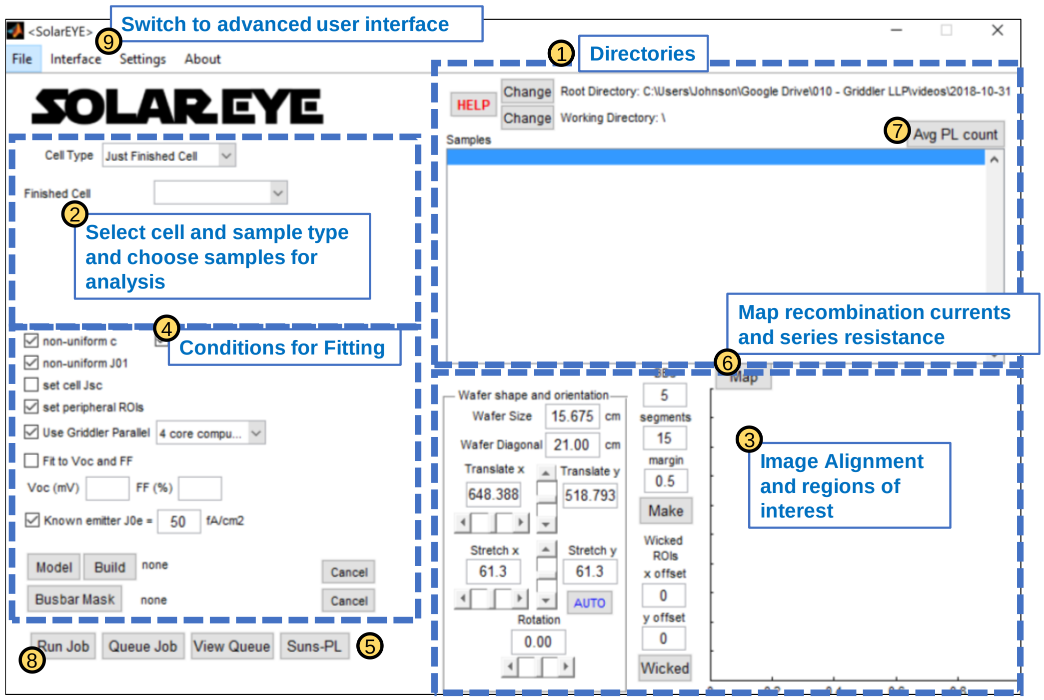
SolarEYE needs either a physical USB dongle provided by us or online activation to run. Either method requires periodic internet connection (for USB dongle about once a month; for online activation about once a day). The USB dongle looks like the one shown below and needs to be plugged into the computer while the program is running.

When you run the program for the first time, if it doesn't detect the USB dongle, then a pop up screen will show up with the option to enter a product key. Use the one provided to you and you can then continue to use the program.



2.2 SOLAREYE Front Page

Upon launching SolarEYE, a splash screen should appear. Wait patiently for the program to launch as for the first time it may require half a minute or so to load the MCR. Below we show the front page of the SolarEYE program.



The front page can be roughly divided into the sections as shown above:

1. Directories and sample listing window (see 3.1).

2. Cell and sample type selector (see 3.2).

3. Luminescence image display screen and manual alignment (see 3.3).

4. Conditions for fitting, model used to fit (see 3.4).

5. (Optional) Suns-PL plot of the sample luminescence data (see 3.5).

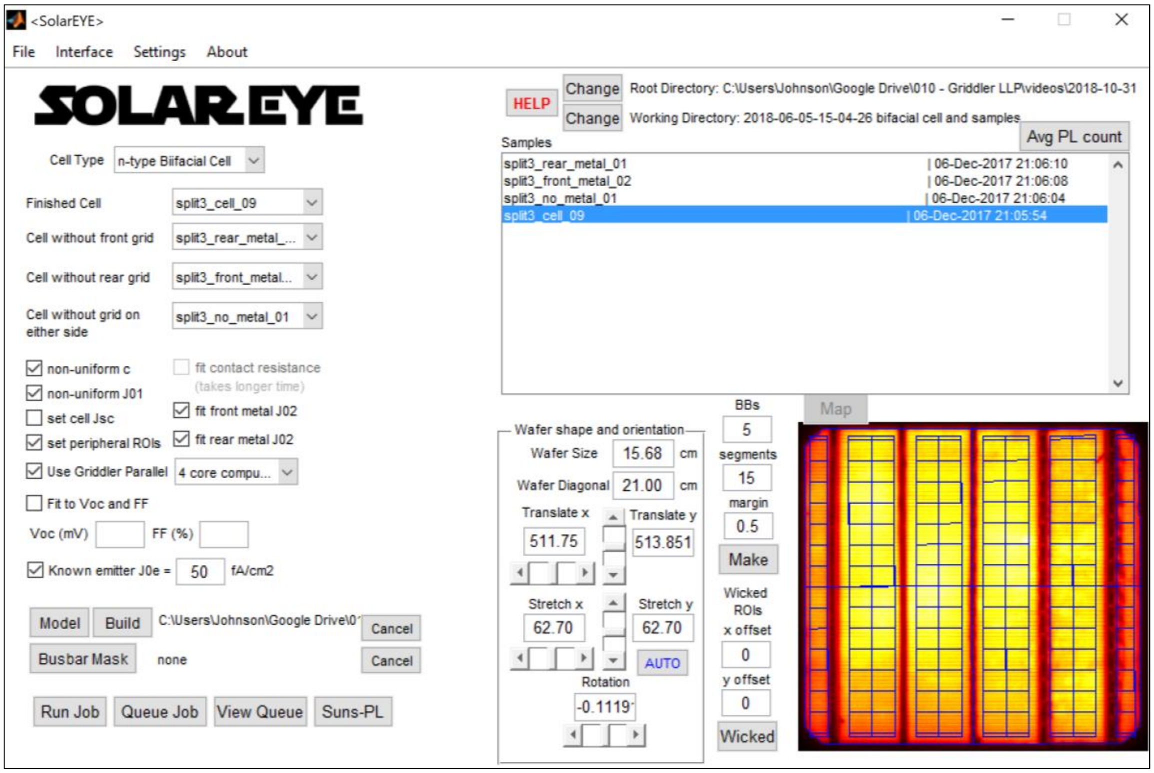
6. (Optional) For samples with luminescence images amenable to recombination currents/series resistance separation, map the spatial distributions of J_0 (saturation current densities), R_s (series resistance), and display the voltage map at open circuit (see 3.6).

7. (Optional) Display list of average PL count for close-to-1-Sun images (normalized to Suns and exposure time), within defined ROIs for all samples in working directory (see 3.7)

8. Run job or queue job (see 3.8).

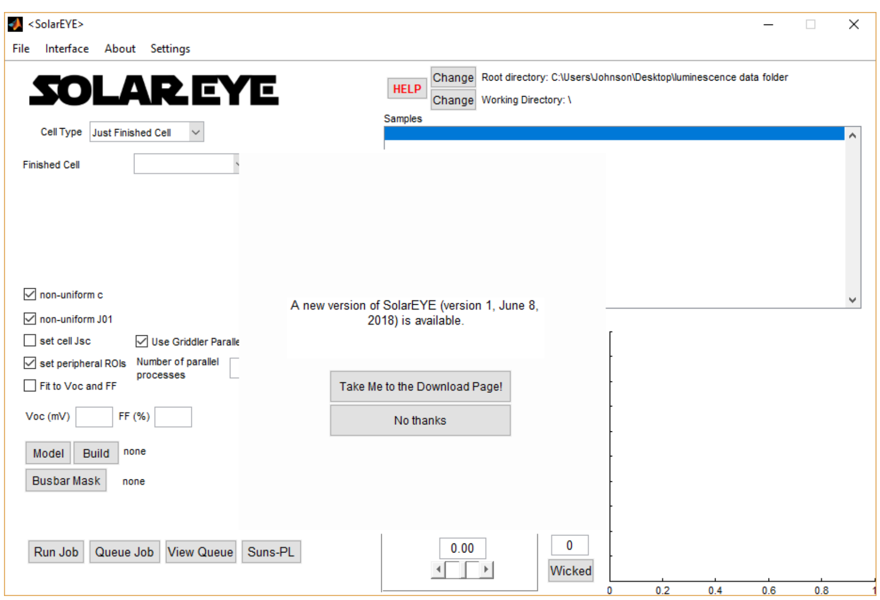
9. Switch between simple and advanced user interfaces (not covered in this manual).

Below we show what the SolarEYE front page typically looks like after the sample directory is listed, and after cell and sample type is chosen and the conditions of fitting have been defined.

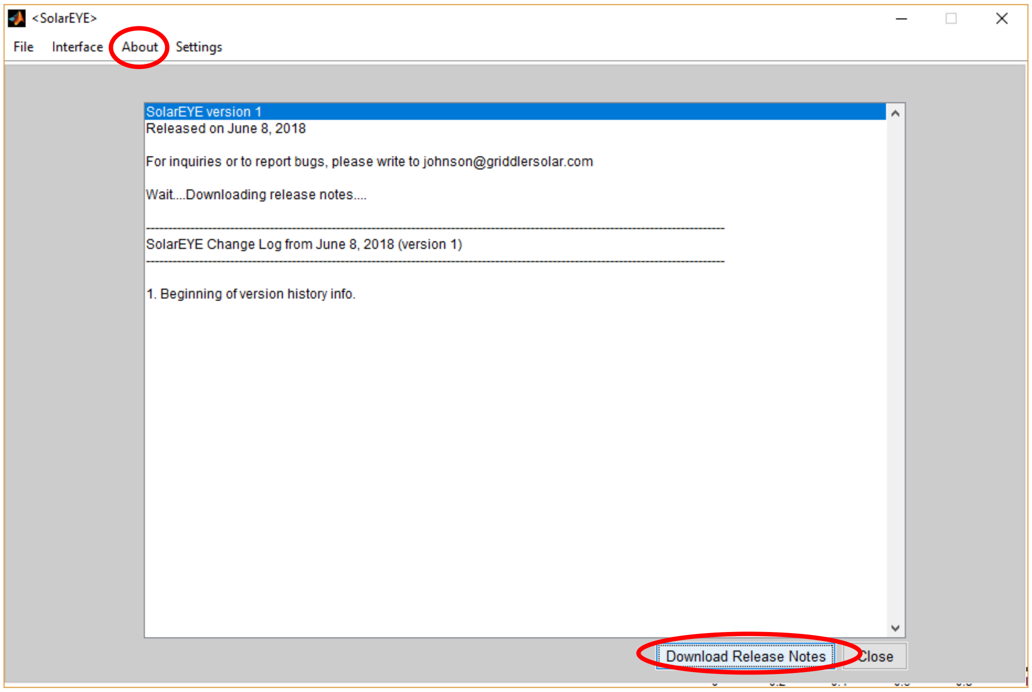


2.3 SOLAREYE Update Notifications

For SolarEYE, we roll out periodic updates, and you'll be notified of one when you reach the simulation page (below). Please be diligent, and click "Take Me to the Download Page" and download the latest installer. You can simply run the installer and it will overwrite the previous SolarEYE version from your computer.



You can always check your version numbers by clicking "About" on the top menu bar. Hit "Download Release Notes" to see the changes made in each version of SolarEYE.

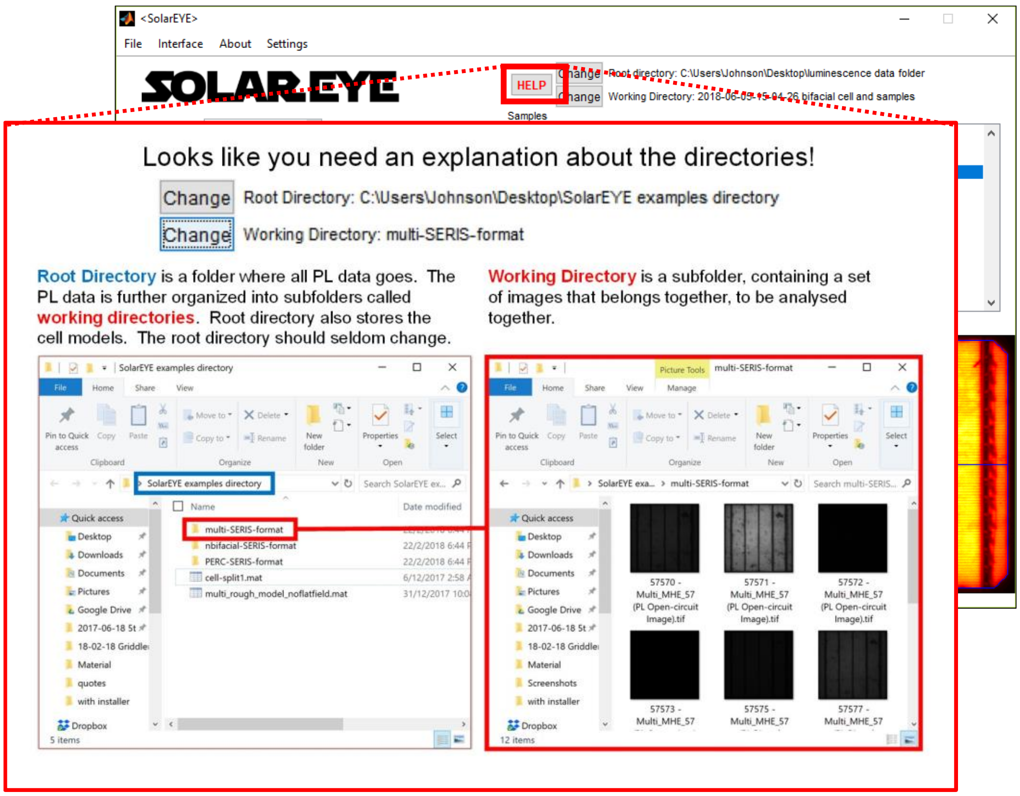


3 Step by Step Guide of Using SOLAREYE Software

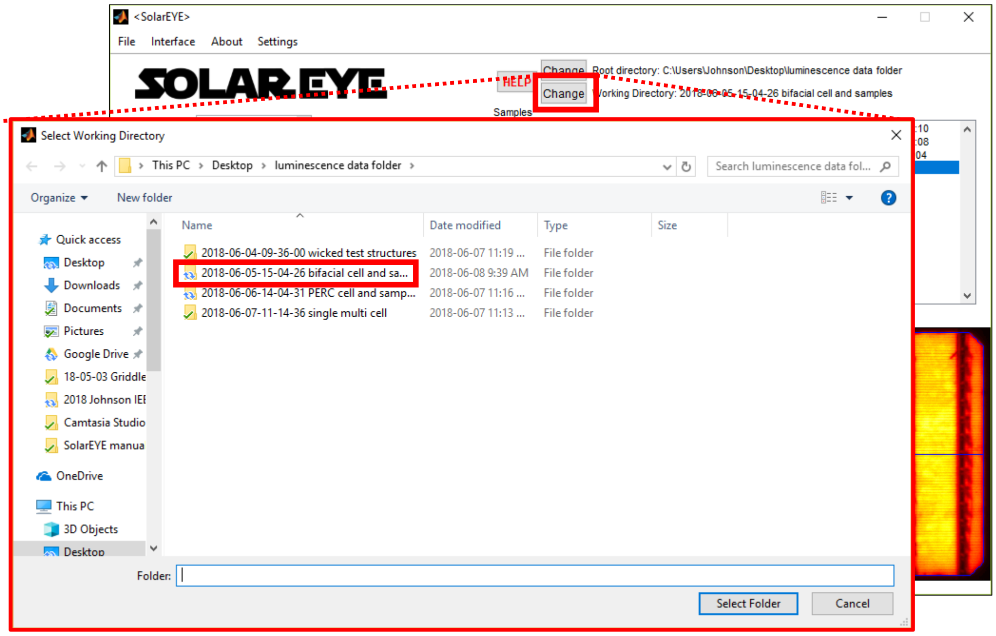
SolarEYE combines luminescence imaging hardware, measurement routine, and the SolarEYE software to parse the images and perform analysis. It is expected that you are running the SolarEYE software on the computer that collects and stores the luminescence images.

3.1 Directories and Samples Listing

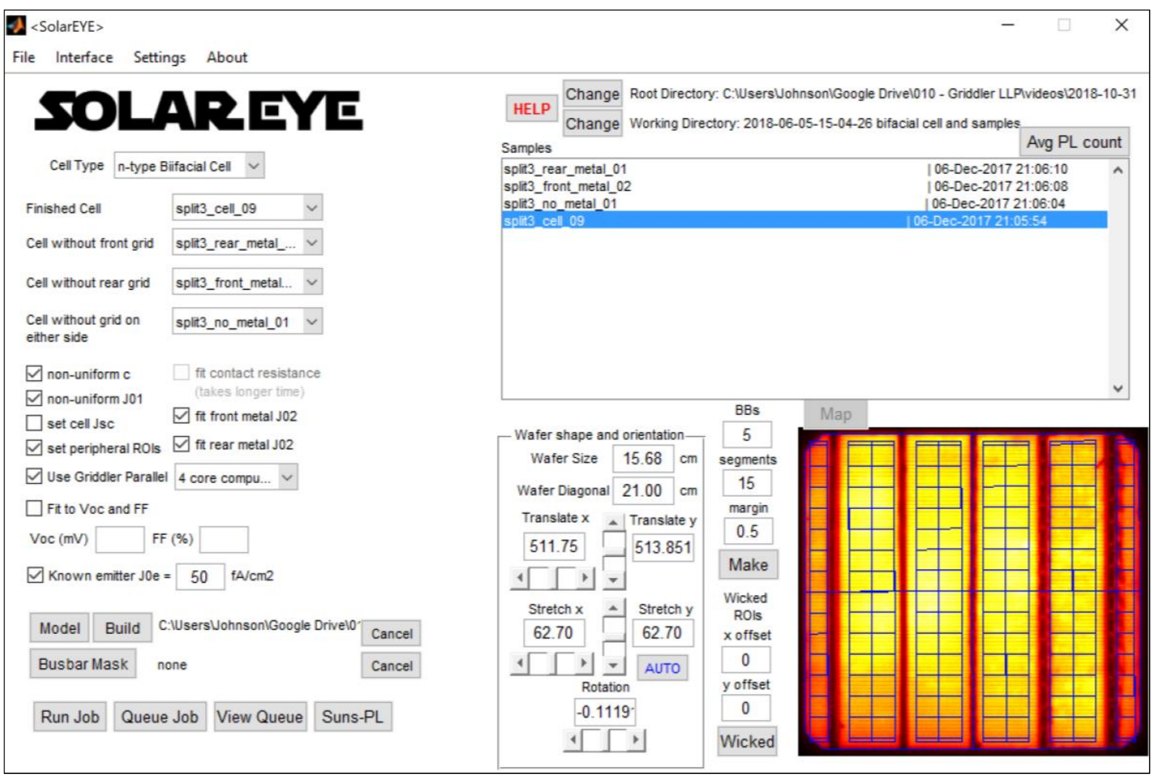
The SolarEYE luminescence imaging measurement routine places all data in a common root folder, and places all data belonging to each series of samples in a separate subfolder. You can always press the HELP button to get an explanation of this file structure.



To select a sample series for analysis. Click "Change" working directory to select one of the folders containing luminescence images of a sample series, previously measured by the luminescence tool.



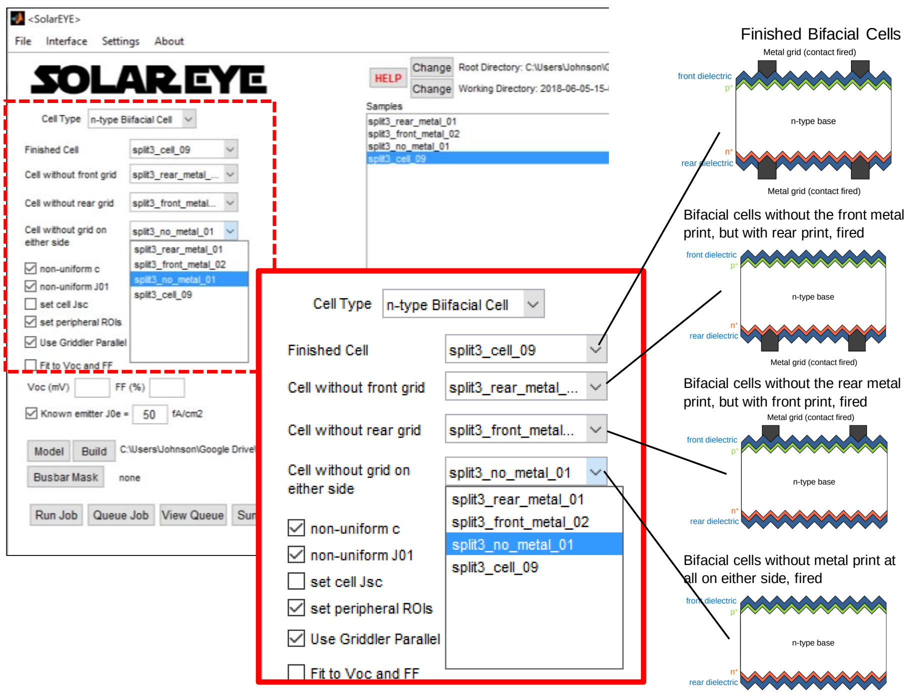
Upon selecting this working directory, SolarEYE will search through the files inside and extract the sample name, luminescence imaging conditions, of each image. It will then list the different sample names contained in the working directory.



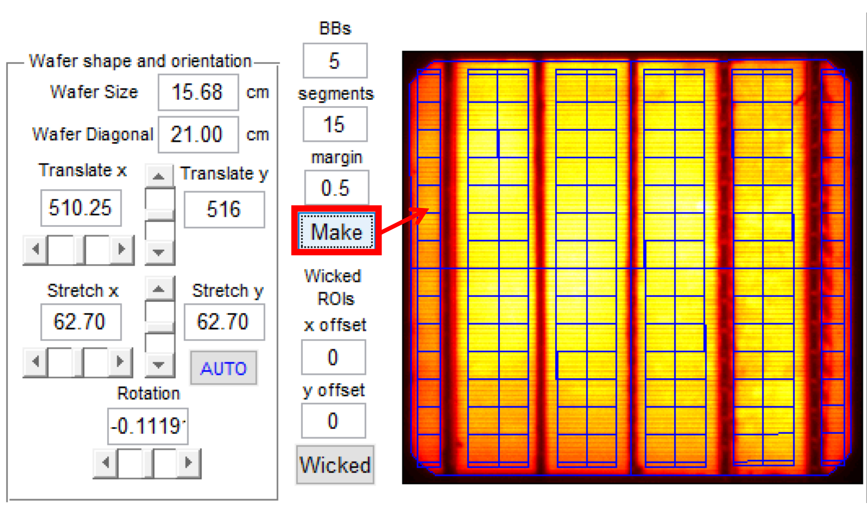
3.2 Cell and Sample Type Selector

The current SolarEYE hardware supports three kinds of measurement routines, depending on what kind of cells you would like to analyze, and what cell parameters you would like to extract. See section 4 for more details.

In the current working directory, the samples form the set that belongs to routine 1 (bifacial cell). So let's go through the procedure of setting up the analysis. In the red box region of the screenshot below, select "Cell Type" = n-type Bifacial Cell. The corresponding sample type names then appear. You must select the correct sample to its type. In the example below, we have "Finished Cell" = split3_cell_09, "Cell without front grid" = split3_rear_metal_01, "Cell without rear grid" = split3_front_metal_02, "Cell without grid on either side" = "split3_no_metal_01".



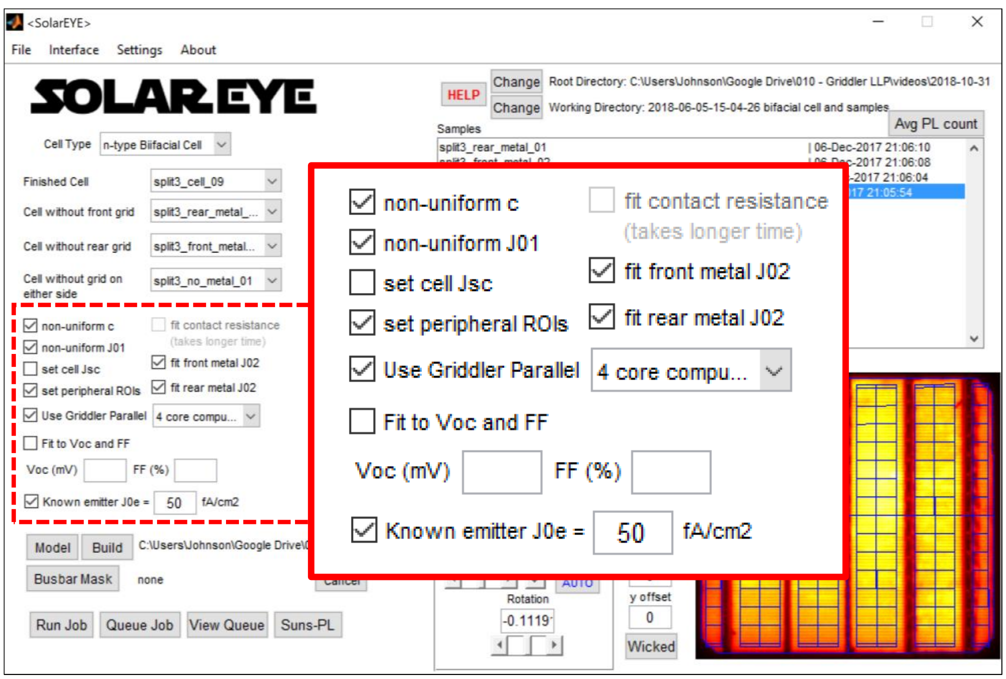
3.3. Luminescence Image Display Screen and Manual Alignment



When you click on a sample in the directory listing, one of the luminescence images for the sample appears in the display screen below. There will also be a blue wafer outline that should more or less contour the wafer image. This wafer outline will define the coordinates of the Griddler model used to simulate the luminescence images in the fitting routine later. SolarEYE tries to autoalign the blue contour to each image, but it is always a good idea o check whether the alignment is good or not. If the alignment is not good, you should choose different values for “Translate x”, “Translate y”, “Rotation” in the above screenshot to get the blue contour into good alignment with the wafer edges.

Referring still to the above screenshot, SolarEYE also will define regions of interests (ROIs) in which the experimental and simulated luminescence intensities will be averaged and compared. Click “Make” in the above screenshot to reveal these regions of interests. It is important that in the field “BBs” you have the correct number of busbars for your cell type. If you have the incorrect number of busbars, then some of the ROIs will land on busbars which would not be good areas for the luminescence intensities to be compared.

3.4. Conditions for Fitting, Model Used to Fit

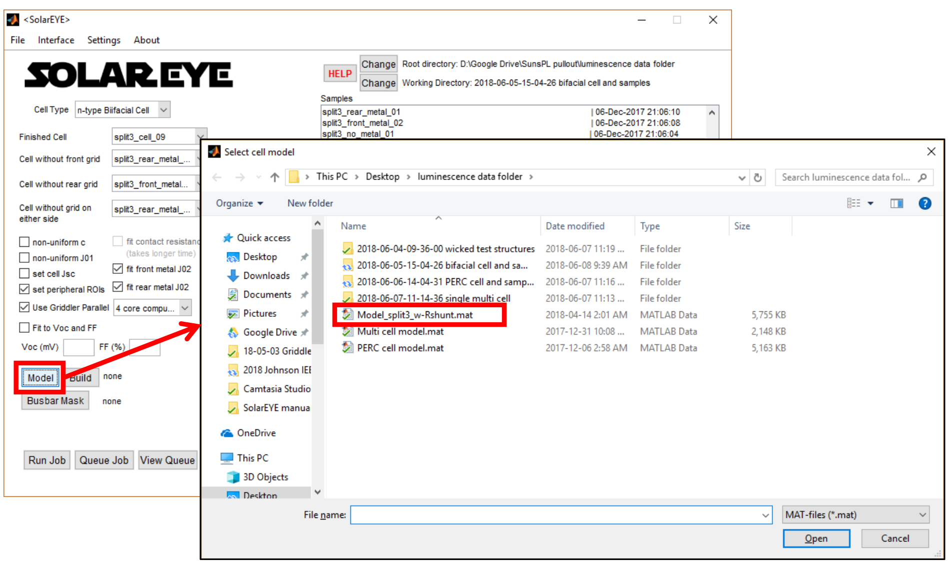


In this section, it is best to start with the default settings. We recommend that you check “non-uniform c” and “non-uniform J_{01}” if your sample is multicrystalline. If you know the expected cell open-circuit voltage (V_{oc}) and fill factor (FF), and you would like the fit to also explain these I-V parameters, then check “Fit to Voc and FF” and then enter the expected V_{oc} and FF into the corresponding boxes.

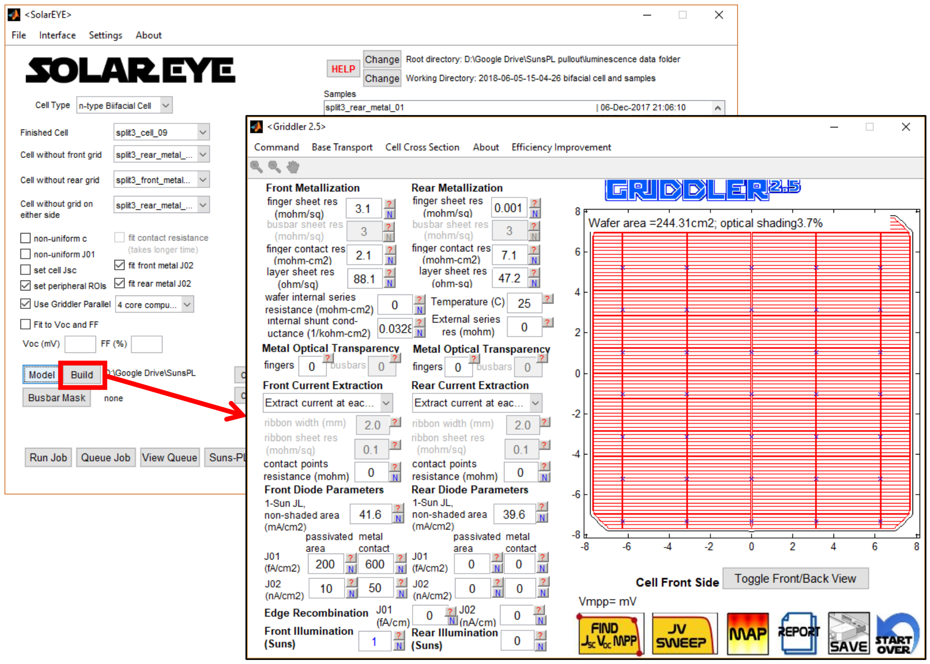
Update since version 3: If the single cell images contain biased-luminescence images that are necessary for contact resistance analysis, then the box (“fit contact resistance”) will be ungreyed and checked. Checking this box enables SolarEYE to fit to the contact resistance. Depending on the cell type (bifacial, or PERC, or Al-BSF cell), the contact resistance represents the sum of all additional resistance not accounted for by the doped layers and metallization grid. For bifacial cells the contact resistance will be the sum of front and rear metal grids contact resistance; for PERC cells the contact resistance will be the sum of front metal grid contact resistance and rear local contact current crowding.

Update since version 8: There is a new box called "Known emitter J_{0e}". This is useful if the user knows the emitter J_{0e} of the solar cell from a separate experiment, such as from a lifetime test of a symmetric passivated emitter sample. Check this box and fill in the known J_{0e} value, and SolarEYE will separate the fitted J_0 in the regions between metallization grid fingers into two parts: the known J_{0e} will become the front passivated region J_{01} in the best fit model, and the remainder (fitted J_{01} – known J_{0e}) will become the base region J_{01} in the best fit model. If the cell type is PERC, then an additional separation of the base region J_{01} into contributing parts by the rear local contact and the rear passivated region will be attempted in the rear local contact calculator page, by tuning the SRV values of the rear local contact and the passivated areas. See Griddler manual v1, P.46 for more details about the local contact calculator.

Next, click "Model" to choose the Griddler cell model that you would like to use to perform the fit. The Griddler cell model should have the same wafer shape, size, and metallization patterns as the actual cell. If you don't have a model ready, then click "Build" to create one from scratch.



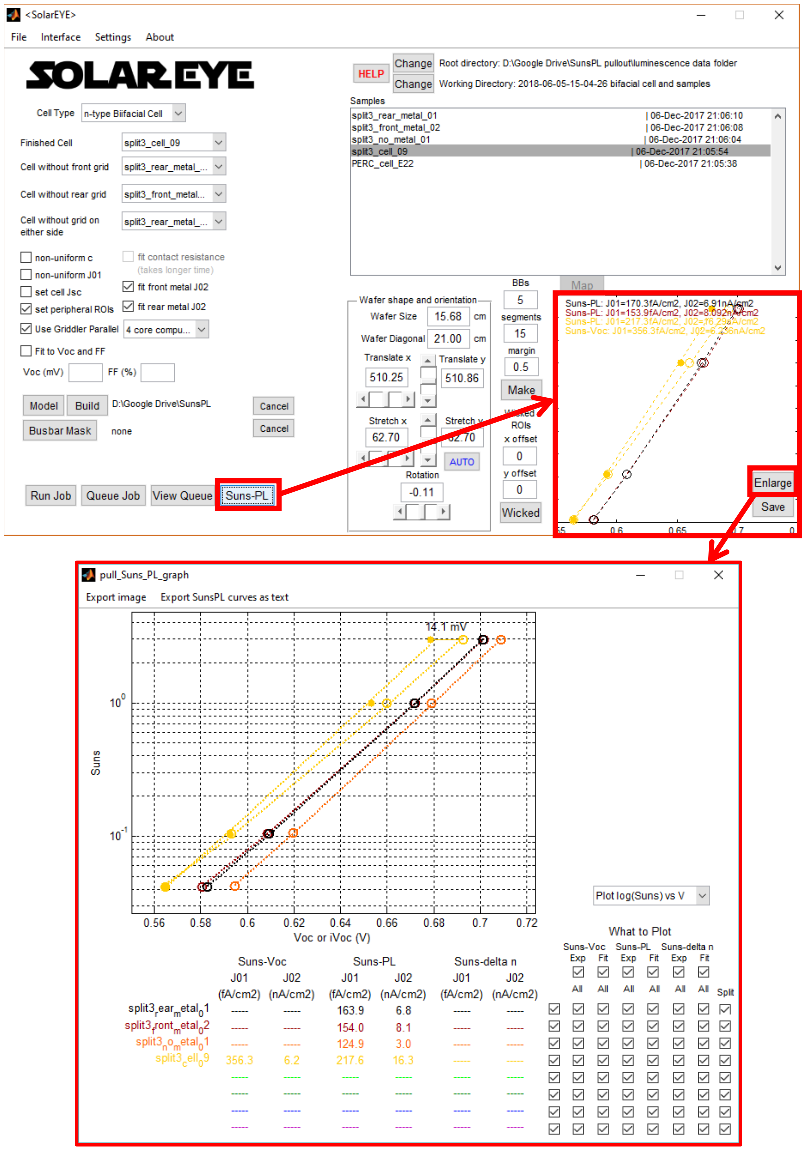
If you click "Build" without loading a model, then Griddler will be launched to allow you to create the cell model from scratch. If you have already selected the model, then clicking "Build" will launch Griddler and Griddler will open the cell model to let you edit it.



3.5. (Optional) Suns-PL plot of the Sample Luminescence Data

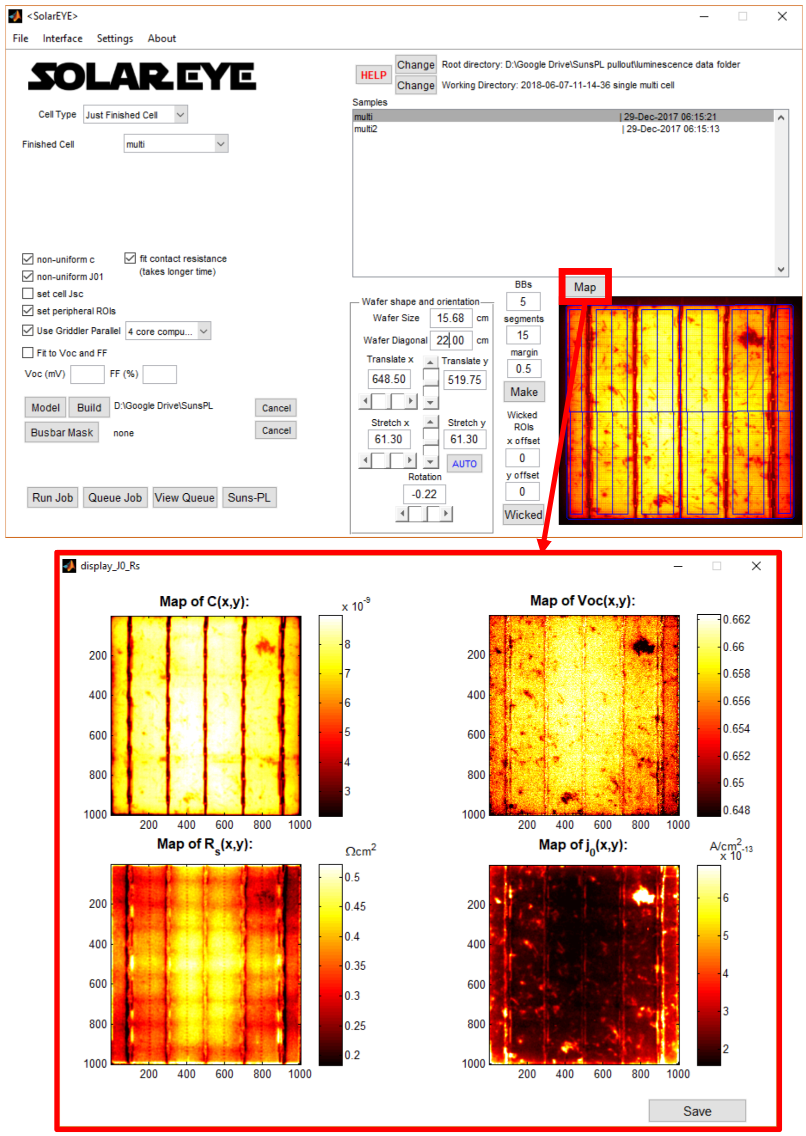
Suns-PL and Suns-Voc are special plots of the samples open-circuit photoluminescence (PL) data. It is a way of visualizing the cell quality and this is an optional step.

Click on “Suns-PL” and SolarEYE will gather the PL images belonging to each sample type, and display the plots. Click “Enlarge” to show the plots in one screen. In this example, the yellow, black, red, orange data points are the voltages against illumination intensity of the four sample types (finished bifacial cell; bifacial cell without the front metal print, but with rear print, fired; bifacial cell without the rear metal print, but with the front print, fired; bifacial cell without metal print at all on either side, fired). Without going into the details, you can see clearly that the voltage of the cell without metal print at all is highest, and that of the finished cell is lowest. This reflects the fact that metallization typically induces recombination losses. The plot window provides fits of each samples Suns-PL curve to J_{01}, J_{02} (see Griddler manual 2.7.5). This gives a rough idea of the contribution of metallization to the recombination currents. We will not go through any arithmetic analysis using these plots here. The SolarEYE auto fitting method using Griddler is a superior method to extract recombination parameters in a rigorous manner.



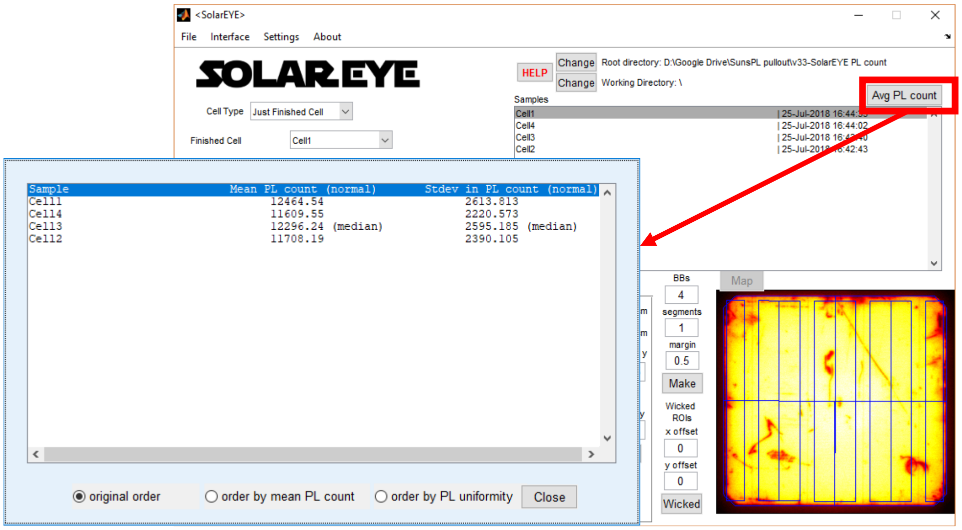
3.6 (Optional) Map Spatial Distributions of J0 (saturation current densities), Rs (series resistance), and display the voltage map at open circuit

For very quick evaluation of cell uniformity in terms of its distribution of recombination currents and series resistance, one can simply select in the list box a cell that has the correct luminescence images for J_0 and R_s separation. At this point, the "Map" button above the cell image will be enabled. Press on this button and a separate window will pop up, displaying four spatial maps: C(x,y), V_{oc}(x,y), R_s(x,y), J_0(x,y). The first is not used for ordinary work. The second (V_{oc}) is a map of the open circuit voltage at 1 Sun. The third (R_s) is a map of the series resistance, and the fourth (J_0) is a map of the saturation current density, which is a representation of the uniformity of the recombination currents. As a rough guide, R_s <= 0.5 ohm-cm^2 everywhere is excellent. R_s <= 1 ohm-cm^2 everywhere is decent but has room for improvement. Cells with areas with unusually high R_s (larger than 5 ohm-cm^2) is an indication of nonuniform contacts. J_0 and V_{oc} maps magnitudes vary from cell type to cell type. One can usually observe the overall uniformity to determine if there are process related issues.



3.7 (Optional) Display list of average PL count for close-to-1-Sun images (normalized to Suns and exposure time), within defined ROIs for all samples in working directory

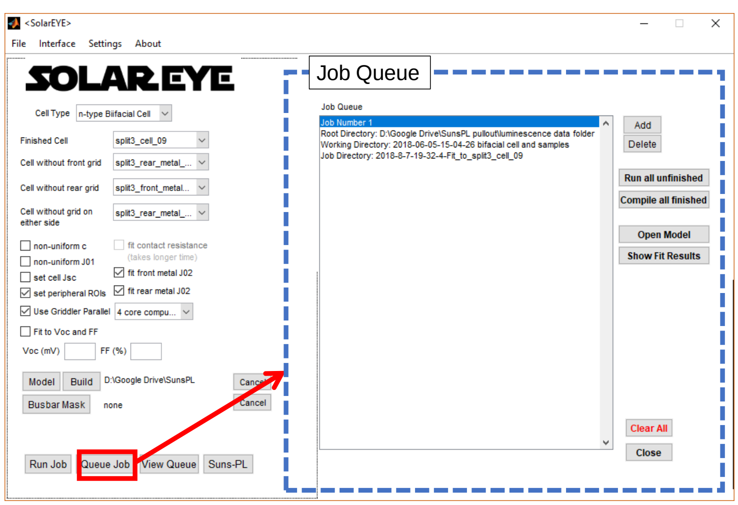
This button allows you to list the average PL count in the regions of interest defined (see blue boxes in the below picture), for all samples within the working directory. The PL counts are selected from images as close to 1 Sun open-circuit condition as possible, and further the PL counts are normalized to 1 Sun and 1s PL image exposure time. This way, you can compare the relative brightness (proxy for voltage) of all samples in the directory. The cell with median PL count and the cell with median standard deviation in PL count are marked (see window in the below picture). We encourage that the user create five of every sample of the same type, and make use of this feature in SolarEYE to first pre-screen the sample PL count to pick out the median valued sample for the full SolarEYE luminescence imaging and auto fitting routine.



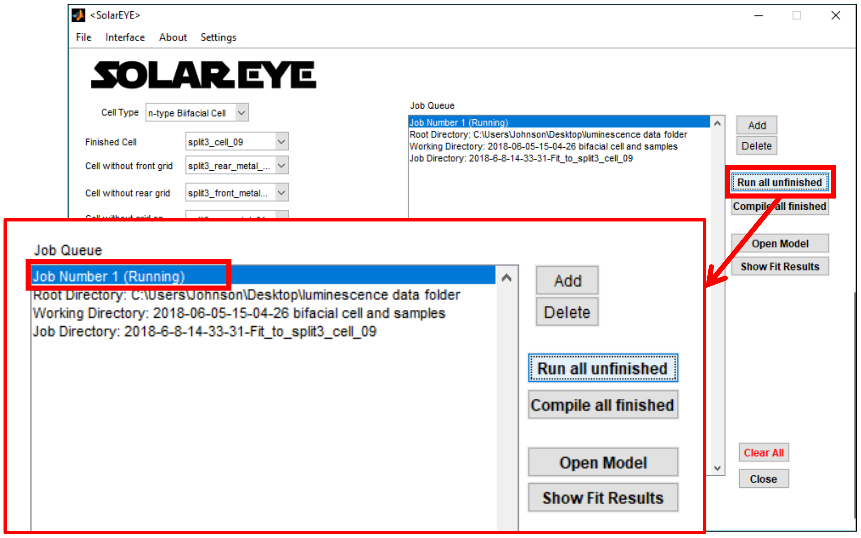
3.8 Run job or queue job

At last, we're ready to run the autofitting of the luminescence images to extract the vital cell parameters. We can do this either by pressing "Run Job" or "Queue Job". "Run Job" will run analysis on the current working directory. "Queue job" allows you to save the analysis instructions in a queue, so that you can for example define the settings to fit many folders, and then ask SolarEYE to fit each folder in the queue one by one. Because one analysis for one folder can take as long as 30 minutes, depending on the computer speed, queue job has the advantage that all the analysis can be done at a block of time (e.g. over night) where there is less demand for the computer usage.

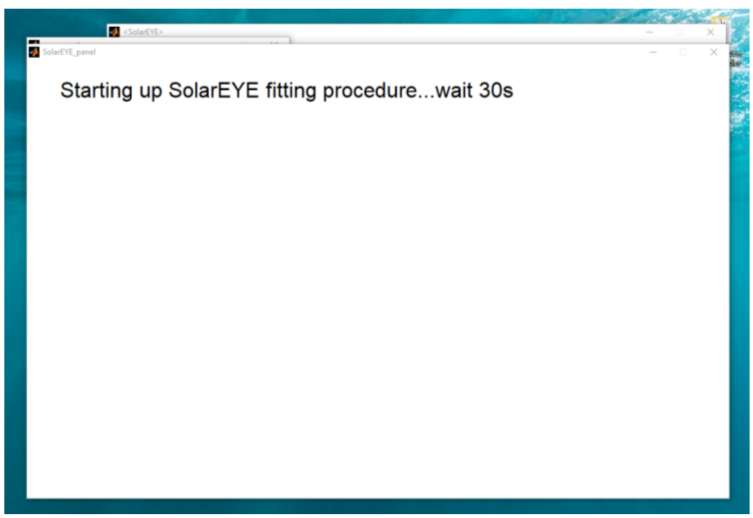
Let's choose "Queue Job", and now the job queue appears on the right. Currently we have one job, with the working directory listed.



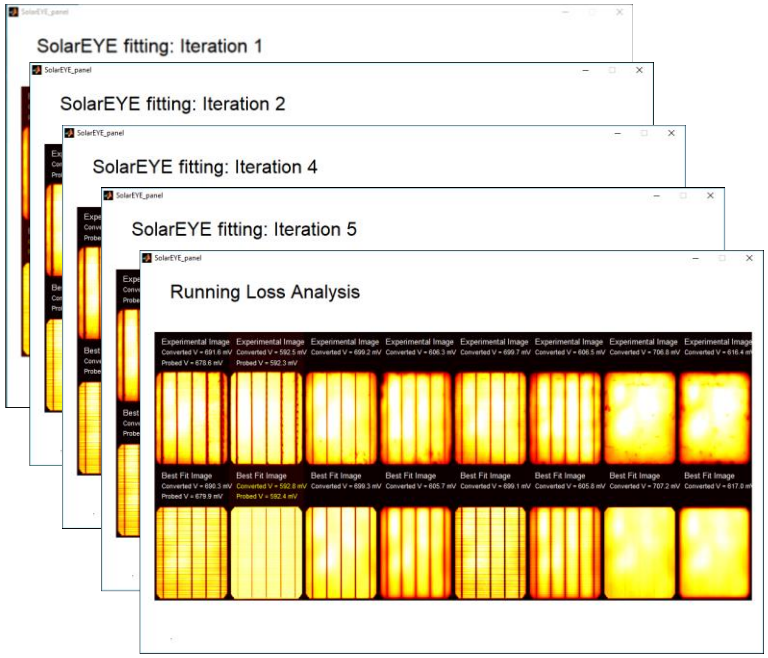
Without creating more jobs, let's click "Run all unfinished". This will trigger SolarEYE to analyze that one working directory for bifacial cells that we have done settings for. When you press "Run all finished", the first job in the queue will show that it is Running. Be patient as it may take some time for any new information to be displayed.



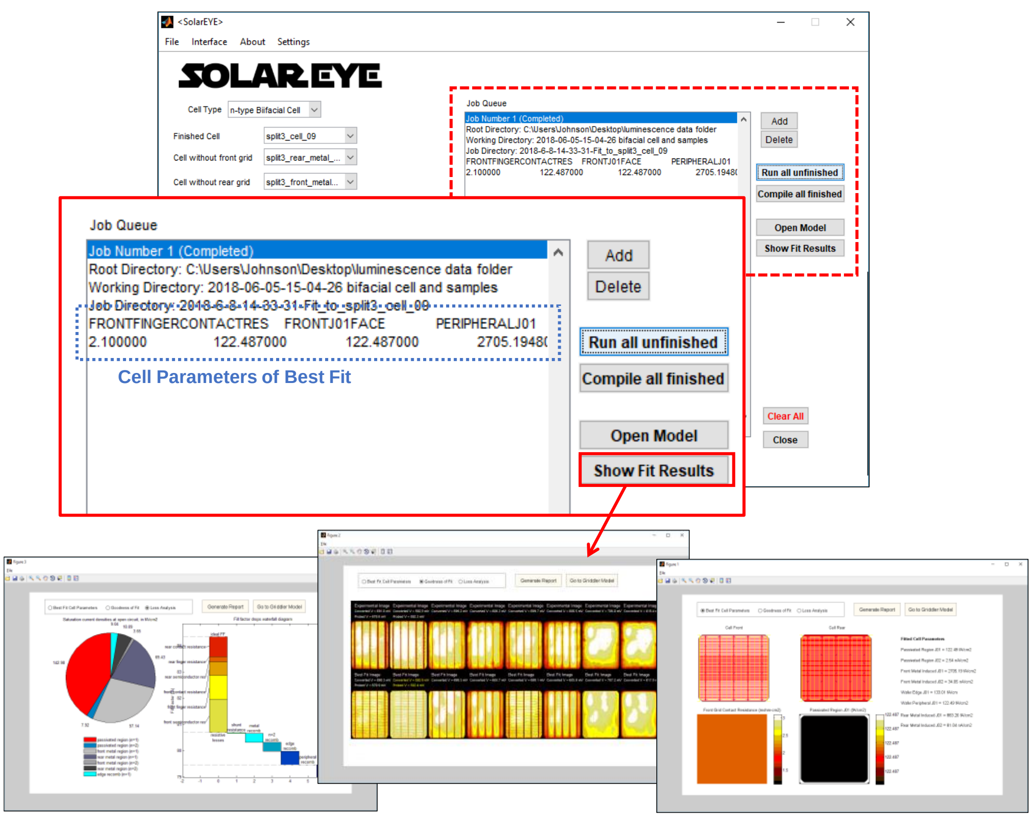
As SolarEYE initiates the analysis, you will see that a screen appears that says "Starting up SolarEYE fitting procedure…wait 30s".



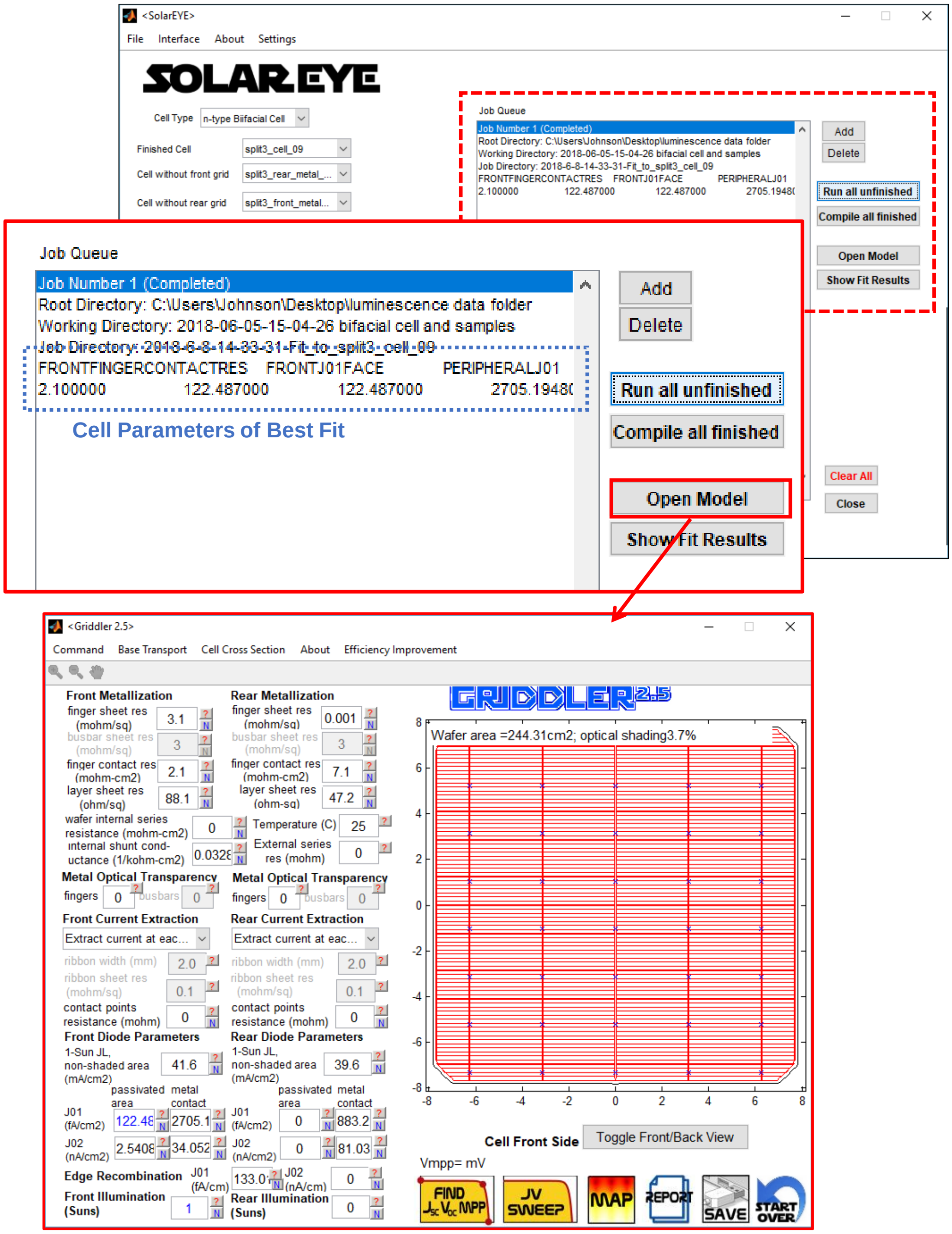
Over the course of 5-30 min, you will see that SolarEYE displays comparison of the experimental luminescence images to the corresponding simulated images, in several iterations of it. Upon obtaining a good fit, SolarEYE will insert the best fit cell parameters into Griddler and run loss analysis. When SolarEYE finishes analyzing, the fit window will close.



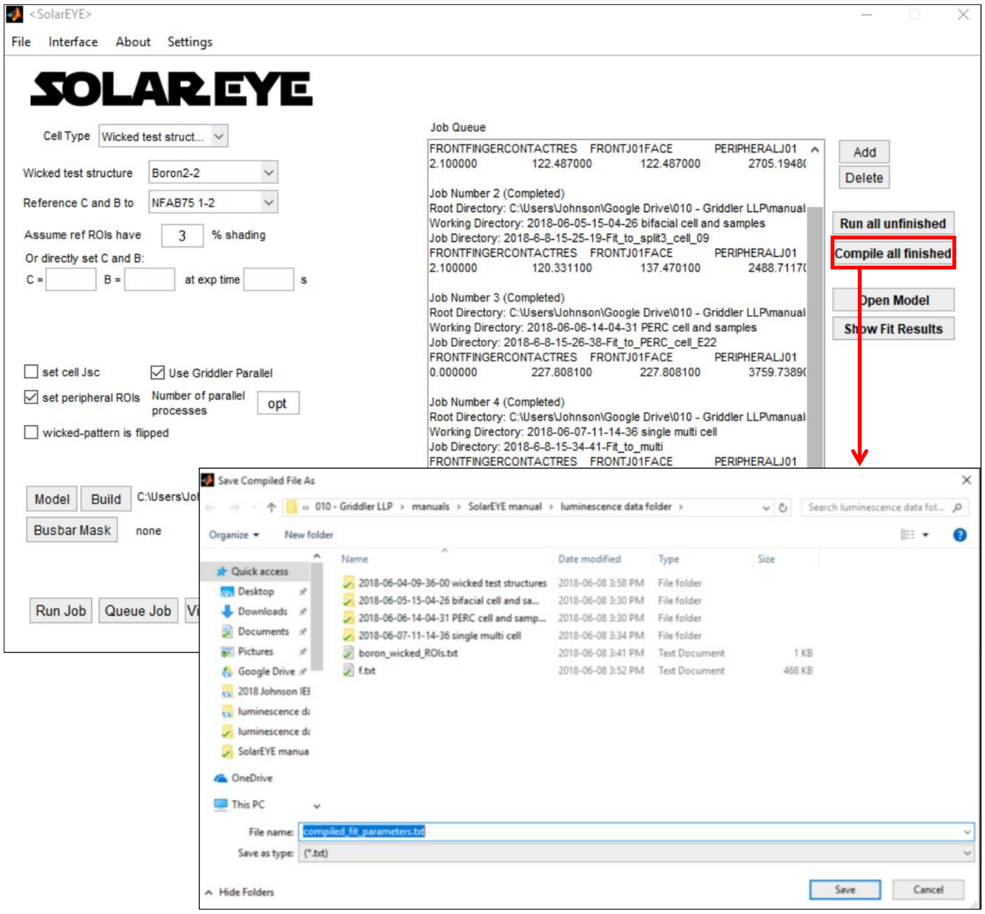
When SolarEYE finishes analyzing, the fit window will close. You'll then see that in the job queue, the job which is finished now says Completed, and the cell parameters of best fit are listed. Now, you can click "Show Fit Results" and SolarEYE will display the loss analysis windows (see Griddler manual 2.8), goodness of fit, and the cell parameters of best fit.



In the job queue, click “Open Model” to launch the Griddler model with the cell parameters of best fit inside.

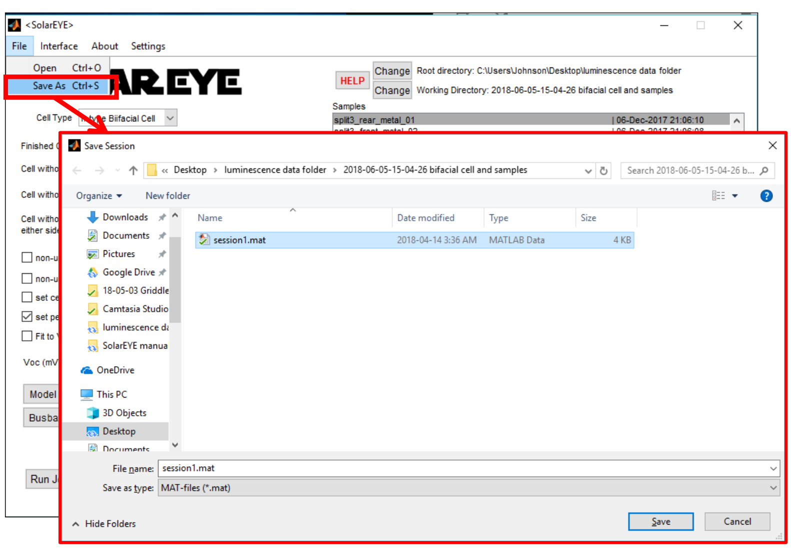


If you have ran multiple jobs, as in the below screenshot, you can compile all the best fit cell parameters of all the jobs into a table for easy comparison.



3.9 Save and Open Session

You can always save the session and open it again later so reload the directory, settings, and queue, via the File menu.



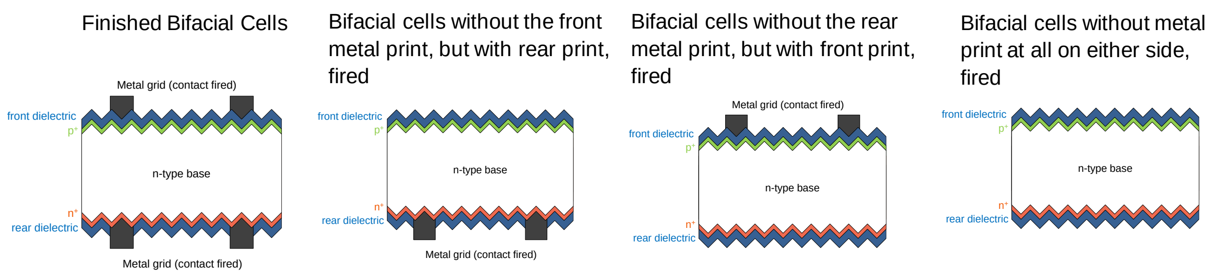
4 Supported SolarEYE Measurement and Analysis Routines

The current SolarEYE hardware supports three kinds of measurement routines, depending on what kind of cells you would like to analyze, and what cell parameters you would like to extract.

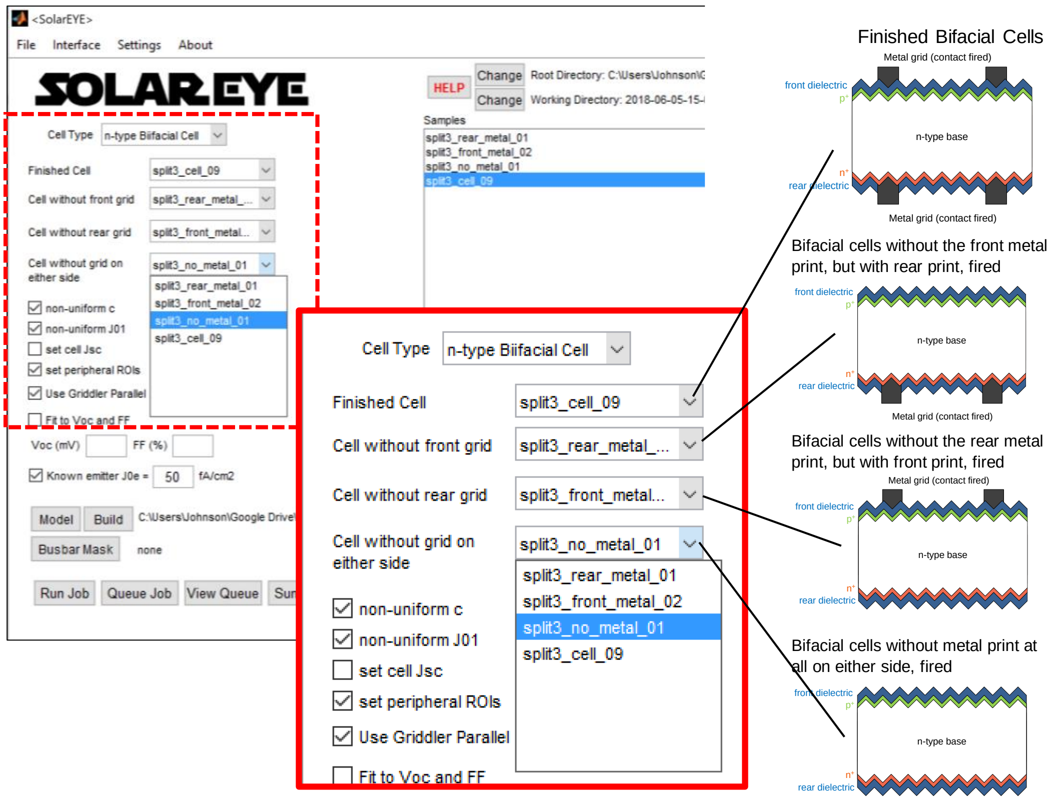
4.1 Bifacial Solar Cells

For bifacial solar cells, one routine requires the following four samples types: 1) finished bifacial cell, 2) bifacial cell without the front metal print, but with rear print, fired; 3) bifacial cell without the rear metal print, but with the front print, fired; 4) bifacial cell without metal print at all on either side, fired. We recommend that you create 5 samples for each type, perform 1 Sun photoluminescence (PL) imaging for each, and pick the sample with the median average PL intensity of each group (**make use of the SolarEYE feature built since version 4 to pre-screen samples 1 Sun PL to select the median sample, see 3.6**). The SolarEYE software will analyze the luminescence images of these four sample types and extract the passivated region J_{01}, J_{02}, front metal induced J_{01}, J_{02}, rear metal induced J_{01}, J_{02}, and the edge recombination J_{01} (see Griddler manual section 2.7.5). It will also extract a parameters called peripheral J_{01} which represents the nonuniform J_{01} close to the edges of the wafer. **Update since version 3**: if the bifacial finished cell has images that are amenable to series resistance separation, then in the conditions for fitting section, "fit contact resistance" check box will be enabled, and checked by default. Keeping this checked will cause SolarEYE to first run the single cell fitting routine (see 4.3) on the finished cell to extract the combined front and rear metal contact resistance, and then retain this resistance to complete the bifacial fitting routine to obtain the recombination current densities. This way, the extracted parameters include the spatial map of the contact resistance too, although it will be a value that represents the combined contributions of the front and rear grids.

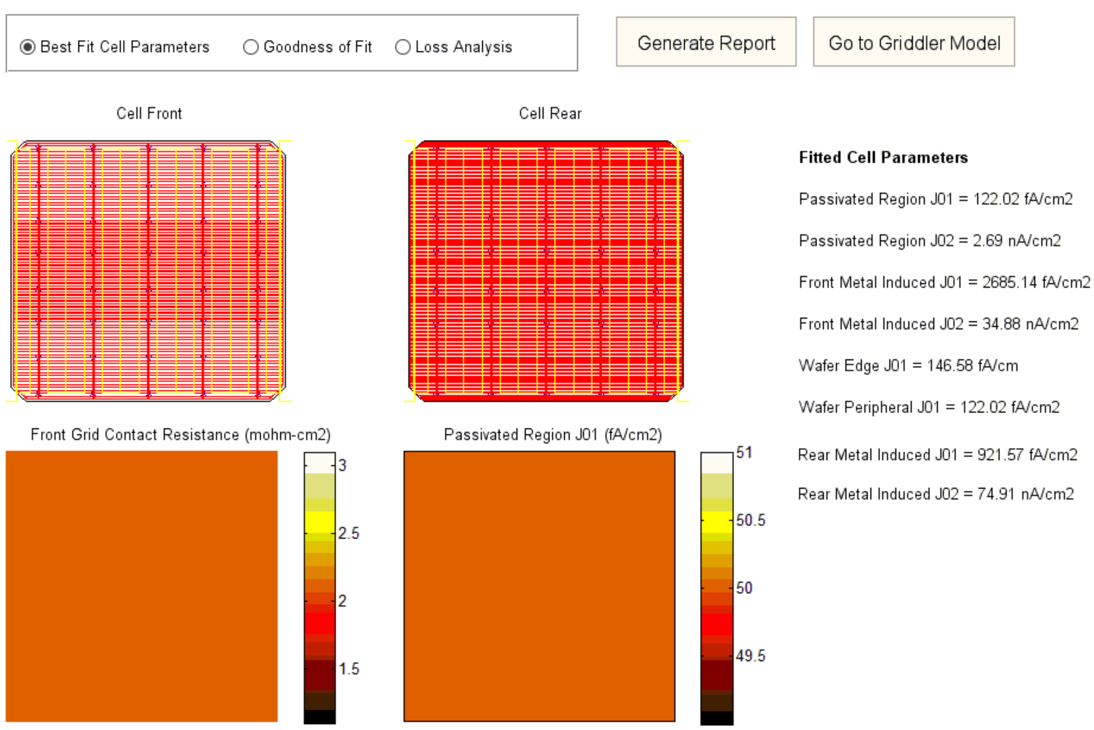
Update since version 8: There is a new box called "Known emitter J_{0e}". This is useful if the user knows the emitter J_{0e} of the solar cell from a separate experiment, such as from a lifetime test of a symmetric passivated emitter sample. Check this box and fill in the known J_{0e} value, and SolarEYE will separate the fitted J_0 in the regions between metallization grid fingers into two parts: the known J_{0e} will become the front passivated region J_{01} in the best fit model, and the remainder (fitted J_{01} – known J_{0e}) will become the base region J_{01} in the best fit model. In the example below, the known emitter J_{0e} is set to 50 fA/cm^2.

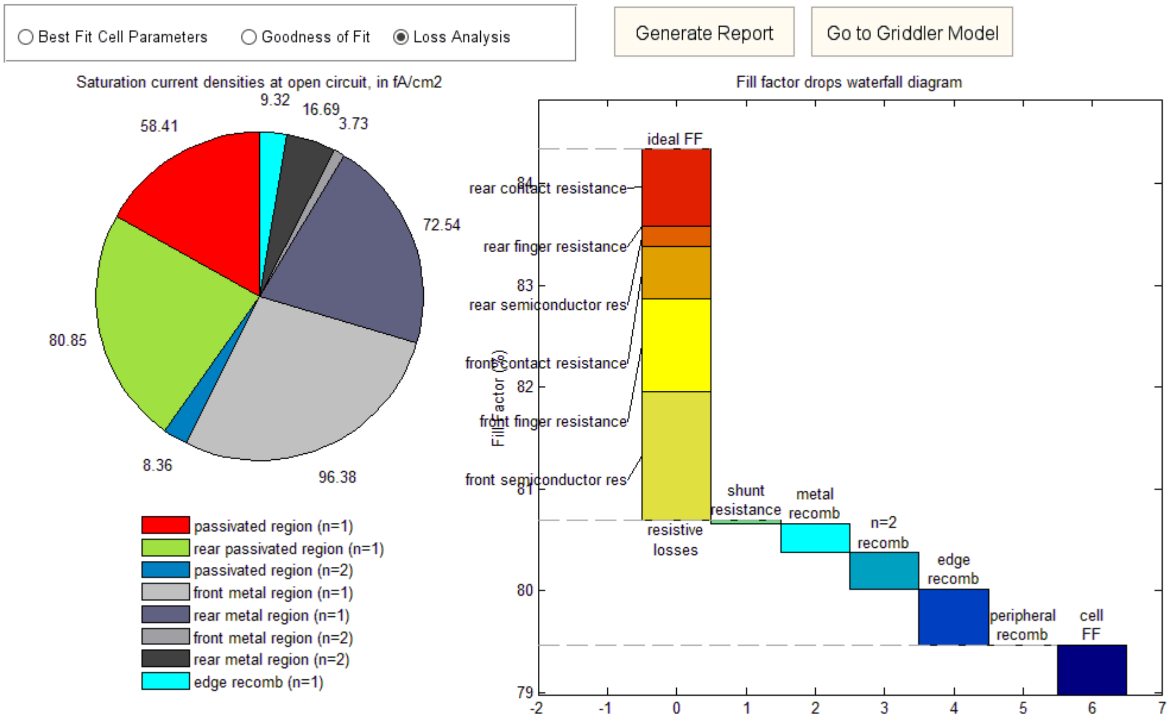


Shown below is the cell and sample type selection window (see 3.2). You must choose "Cell Type" = n-type bifacial cell. The corresponding sample type names then appear. You must select the correct sample to its type.

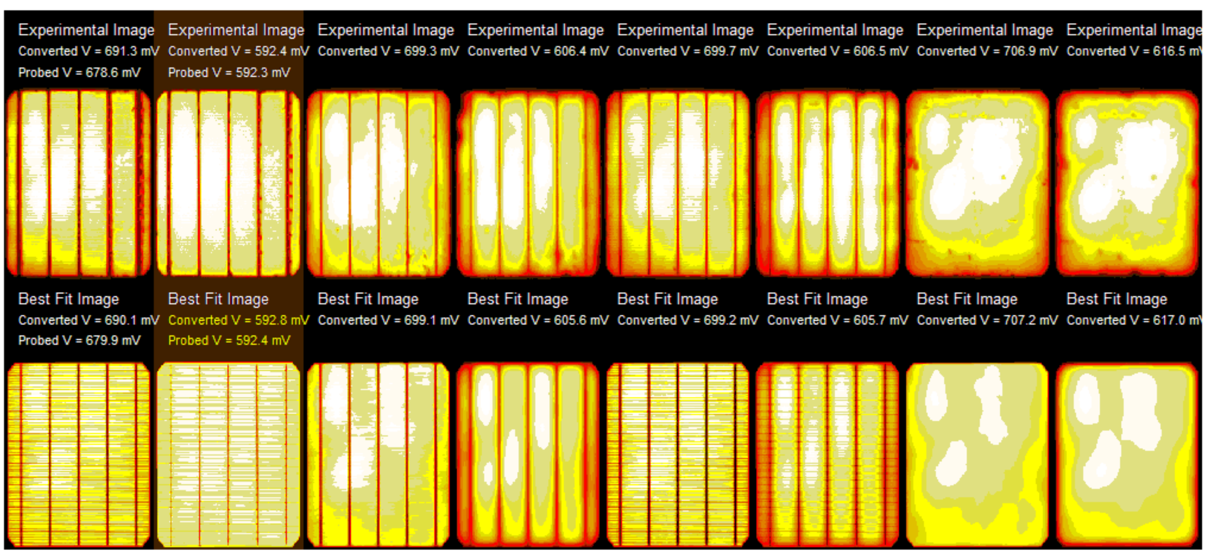


Shown below are typical loss charts, goodness of fit display, and best fit cell parameter page for the bifacial solar cell analysis routine.





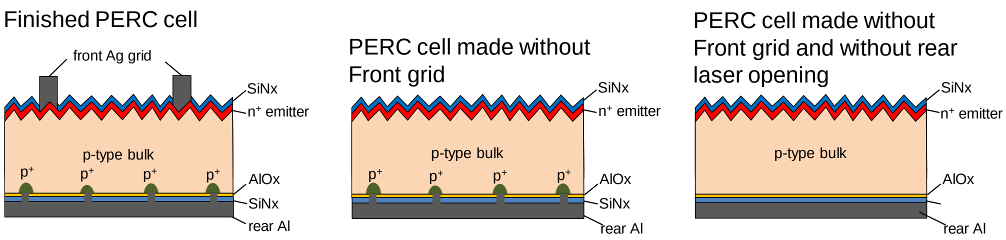
SolarEYE fitting: Iteration 5



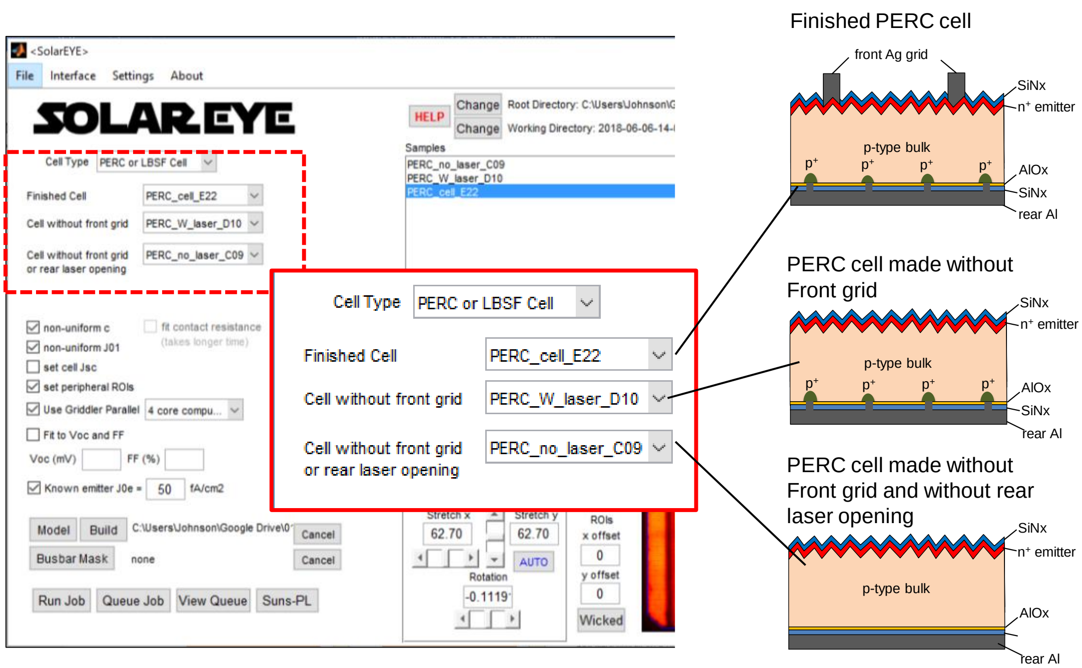
4.2 PERC Solar Cells

For PERC solar cells, the second routine requires the following three samples types: 1) finished PERC cell, 2) PERC cell made without the front grid, fired; 3) PERC cell made without front grid and without rear laser opening, fired. We recommend that you create 5 samples for each type, perform 1 Sun photoluminescence (PL) imaging for each, and pick the sample with the median average PL intensity of each group (**make use of the SolarEYE feature built since version 4 to pre-screen samples 1 Sun PL to select the median sample, see 3.6**). The SolarEYE software will analyze the luminescence images of these three sample types and extract the passivated region J_{01}, J_{02}, front metal induced J_{01}, J_{02}, rear metal contact induced J_{01}, J_{02}, and the edge recombination J_{01} (see Griddler manual section 2.7.5). It will also extract a parameters called peripheral J_{01} which represents the nonuniform J_{01} close to the edges of the wafer. **Update since version 3**: if the PERC finished cell has images that are amenable to series resistance separation, then in the conditions for fitting section, “fit contact resistance” check box will be enabled, and checked by default. Keeping this checked will cause SolarEYE to first run the single cell fitting routine (see 4.3) on the finished cell to extract the combined front and rear metal contact resistance, and then retain this resistance to complete the PERC fitting routine to obtain the recombination current densities. This way, the extracted parameters include the spatial map of the contact resistance too, although it will be a value that represents the combined contributions of the front grid and the rear local contacts.

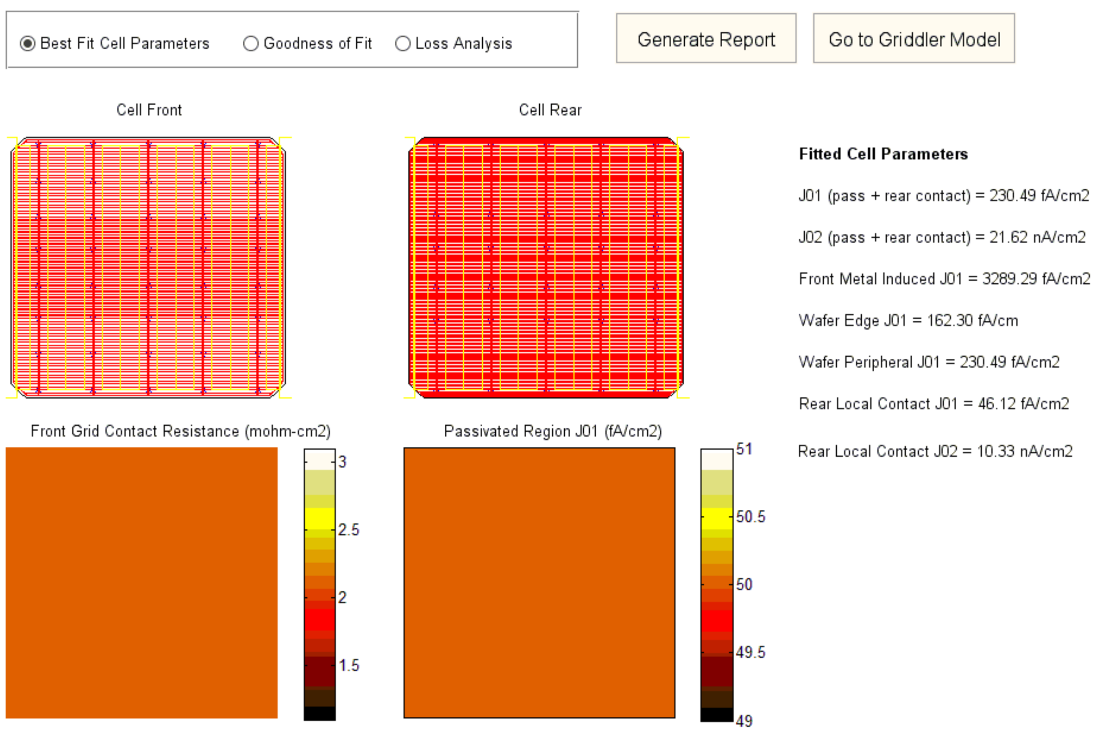
Update since version 8: There is a new box called “Known emitter J_{0e}”. This is useful if the user knows the emitter J_{0e} of the solar cell from a separate experiment, such as from a lifetime test of a symmetric passivated emitter sample. Check this box and fill in the known J_{0e} value, and SolarEYE will separate the fitted J_0 in the regions between metallization grid fingers into two parts: the known J_{0e} will become the front passivated region J_{01} in the best fit model, and the remainder (fitted J_{01} – known J_{0e}) will become the base region J_{01} in the best fit model. In the example below, the known emitter J_{0e} is set to 50 fA/cm^2. Since the cell type is PERC, then an additional separation of the base region J_{01} into contributing parts by the rear local contact and the rear passivated region will be attempted in the rear local contact calculator page, by tuning the SRV values of the rear local contact and the passivated areas. See Griddler manual v1, P.46 for more details about the local contact calculator.



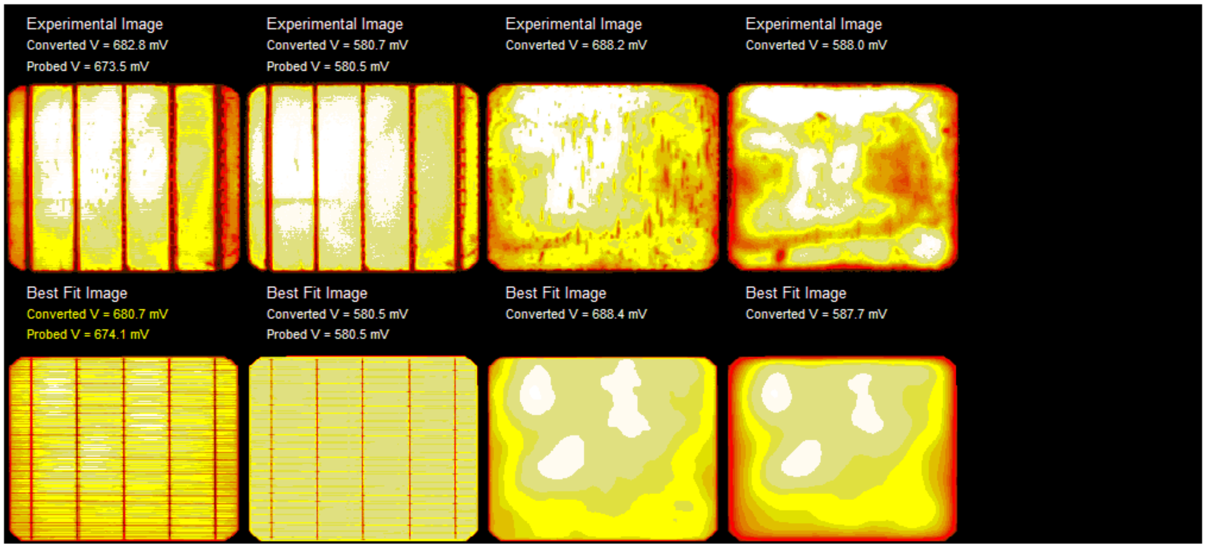
Shown below is the cell and sample type selection window (see 3.2). You must choose “Cell Type” = PERC or LBSF cell. The corresponding sample type names then appear. You must select the correct sample to its type.



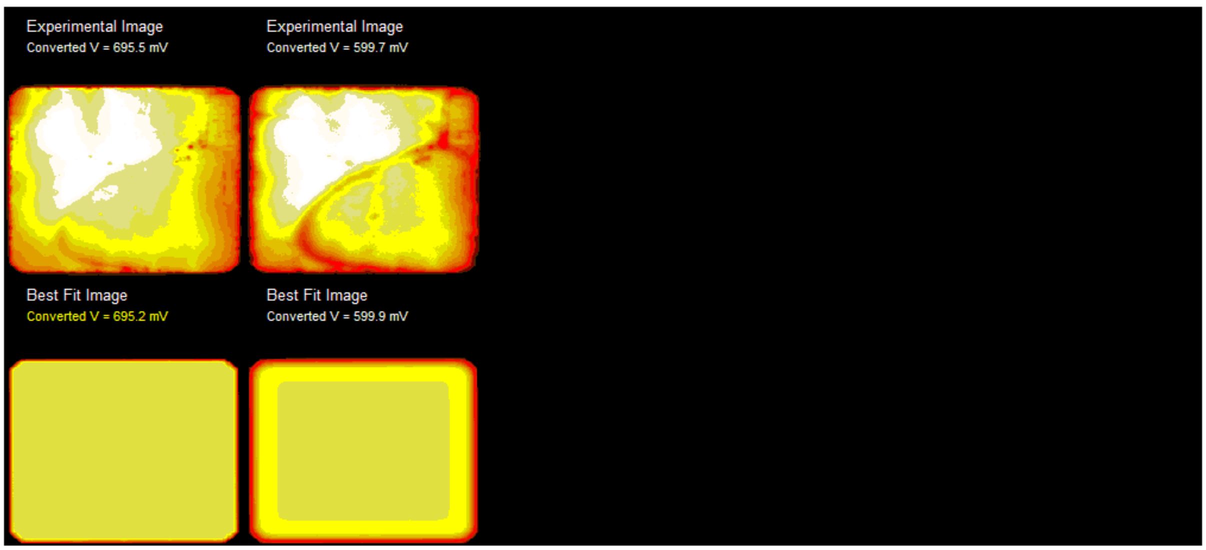
Shown below are typical loss charts, goodness of fit display, and best fit cell parameter page for the PERC solar cell analysis routine.

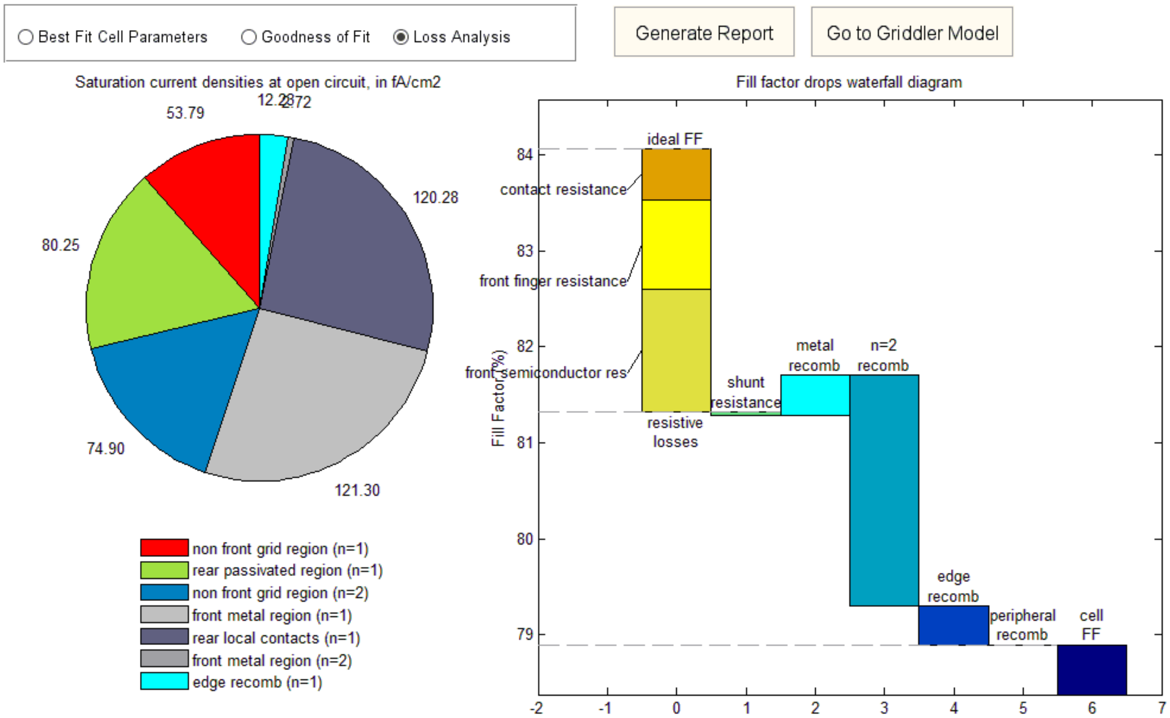


SolarEYE fitting: Iteration 7



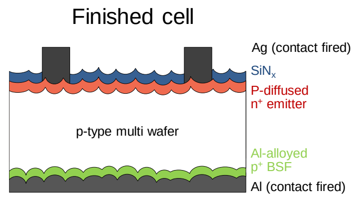
SolarEYE fitting: Iteration 4




Best Fit Cell Parameters
Goodness of Fit
Loss Analysis
Generate Report
Go to Griddler Model
Saturation current densities at open circuit, in fA/cm2
53.79
120.28
80.25
74.90
121.30
non front grid region (n=1)
rear passivated region (n=1)
non front grid region (n=2)
front metal region (n=1)
rear local contacts (n=1)
front metal region (n=2)
edge recomb (n=1)
Fill factor drops waterfall diagram
Fill Factor (%)
ideal FF
contact resistance
front finger resistance
front semiconductor res
resistive losses
shunt resistance
metal recomb
n=2 recomb
edge recomb
peripheral recomb
cell FF

4.3 Single Solar Cells

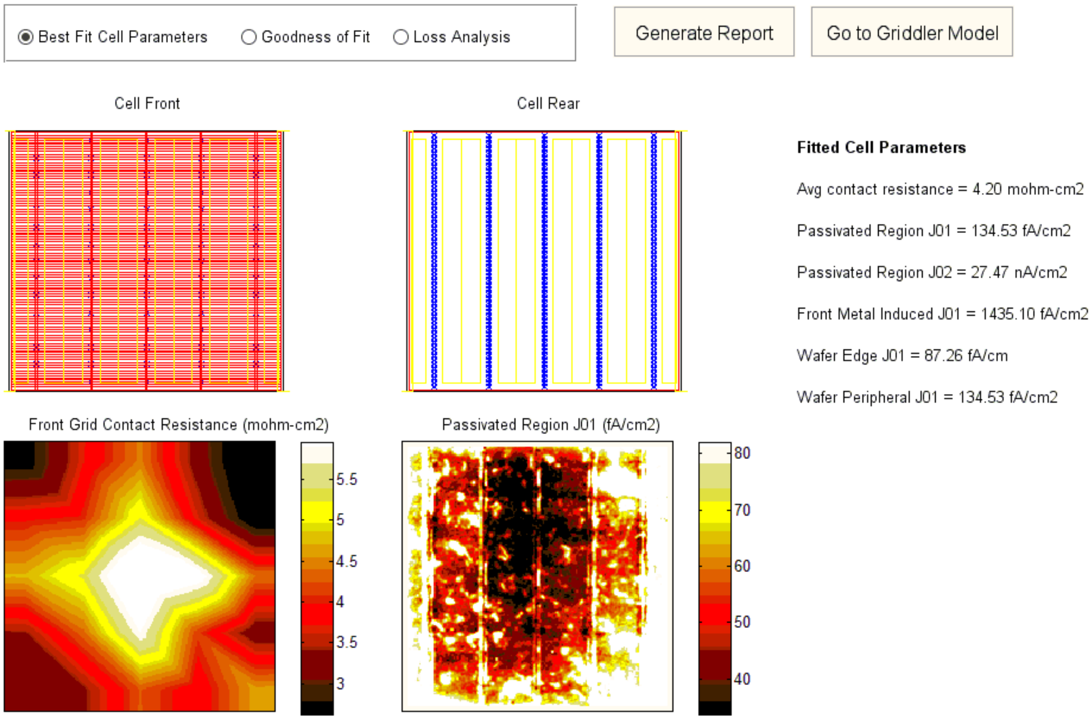
For Al-BSF solar cells, or if you have only single cell as sample, the third routine requires only the finished cell. The SolarEYE software will analyze the luminescence images extract the passivated region J_{01}, J_{02}, front metal induced J_{01}, J_{02}, and the edge recombination J_{01} (see Griddler manual section 2.7.5). It will also extract a parameters called peripheral J_{01} which represents the nonuniform J_{01} close to the edges of the wafer. It will also extract the spatial distribution of the grid contact resistance.



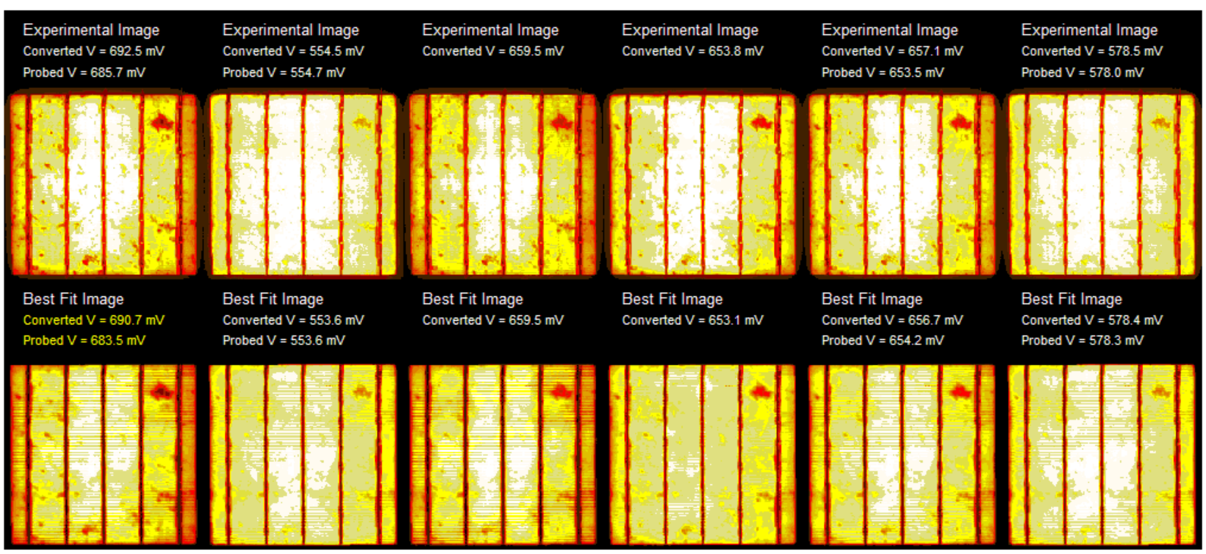
Shown below is the cell and sample type selection window (see 3.2). You must choose "Cell Type" = Just finished cell. The corresponding sample type names then appear. You must select the correct sample to its type. If the cell is multicrystalline, we also recommend checking the "non-uniform C" and "non-uniform J0" boxes, so that nonuniform spatial distributions in the luminescence calibration constant and recombination currents will be used in the fit.

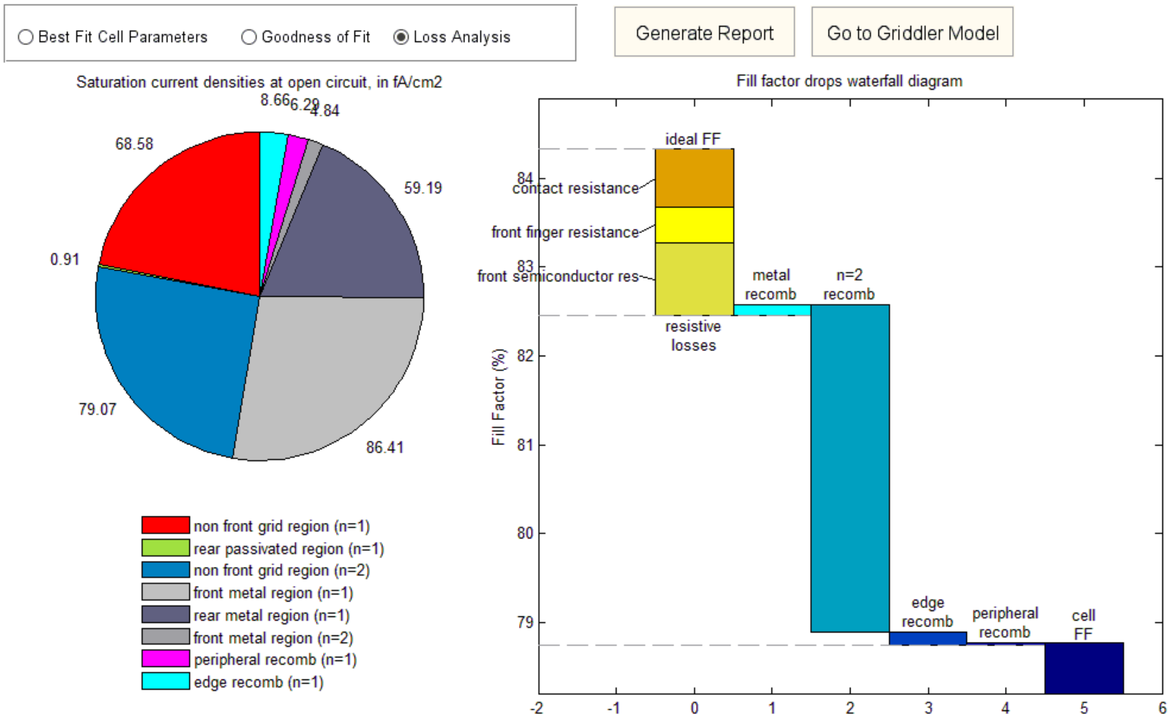
Update since version 8: There is a new box called "Known emitter J_{0e}". This is useful if the user knows the emitter J_{0e} of the solar cell from a separate experiment, such as from a lifetime test of a symmetric passivated emitter sample. Check this box and fill in the known J_{0e} value, and SolarEYE will separate the fitted J_0 in the regions between metallization grid fingers into two parts: the known J_{0e} will become the front passivated region J_{01} in the best fit model, and the remainder (fitted J_{01} – known J_{0e}) will become the base region J_{01} in the best fit model. In the example below, the known emitter J_{0e} is set to 80 fA/cm^2.

Shown below are typical loss charts, goodness of fit display, and best fit cell parameter page for the single solar cell analysis routine.



SolarEYE fitting: Iteration 8




Best Fit Cell Parameters
Goodness of Fit
Loss Analysis
Generate Report
Go to Griddler Model
Saturation current densities at open circuit, in fA/cm2
8.66
6.29
4.84
68.58
59.19
0.91
79.07
86.41
non front grid region (n=1)
rear passivated region (n=1)
non front grid region (n=2)
front metal region (n=1)
rear metal region (n=1)
front metal region (n=2)
peripheral recomb (n=1)
edge recomb (n=1)
Fill factor drops waterfall diagram
ideal FF
contact resistance
front finger resistance
front semiconductor res
resistive losses
metal recomb
n=2 recomb
edge recomb
peripheral recomb
cell FF
Fill Factor (%)