Documentation, PC1D for Matlab

Introduction

This is a documentation file for the *PC1D for Matlab* graphical user interface (GUI), explaining the main features and possibilities of the program, and giving some details about the calculations that have been implemented. For a more comprehensive motivation and simulation examples, readers are referred to the conference paper presented at the 3rd SiliconPV conference in Hameln, 2013 [1]. More details about the simulations can also be found in the source code of the program.

Toolbar buttons

This section gives a description of the different buttons that are placed on the toolbar in the *PC1D for Matlab* GUI. A short description can also be seen by hovering the mouse cursor over the buttons in the program. Most of these functions are also available in the dropdown menus at the top of the GUI.

Parameters are set to standard PC1D settings and saved as new.prm

Open existing .prm file

Save .prm file with same file name

Save .prm with a new file name

Open current .prm file in the original PC1D user interface with a temporary file name called “temp.prm”. Save and close PC1D to continue using the *PC1D for Matlab* interface. The active (last opened) .prm file will not be affected.

Load simulations results from .mat file. This selected results are loaded into memory, and can be selected and plotted as usual. This option can be used to save time when performing time-consuming simulations.

Save simulation results to file. The files are saved in .mat format, which is used by Matlab to store different types of workspace variables. The results can then be loaded at a later time (see above). Note that the simulation parameters are not saved.

Save simulation results to text file. PC1D output data are saved in tab-separated columns. For batch simulations using IV output, columns with J_{sc}, V_{oc}, FF and efficiency are also written at the beginning of the file.

Copy figure data to clipboard. The data plotted in the GUI axes are copied as tab-separated columns to the system clipboard. The n curves in the figure are copied as *[Xdata_1 Ydata_1 Xdata_2 Ydata_2 … Xdata_n Ydata_n]*

Increase the font size of all text objects. Often useful after resizing the GUI.

Decrease the font size of all text objects. Often useful after resizing the GUI.

Change the background color of the GUI using Matlab's interactive color selection.

Zoom in on the figure shown on the right hand side of the GUI. Click once to zoom around clicked point, or drag to zoom to a region.

Zoom out on the GUI figure.

Pan in the GUI figure.

Rotate the GUI figure in 3D.

Add data cursor in the GUI figure, showing the X and Y coordinates of the selected data point.

Add a legend to the GUI figure.

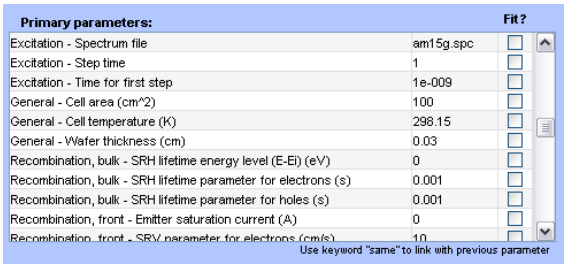
Add a colorbar to the GUI figure. Mostly relevant after plotting colormaps showing the results of 2 parameter variations.

Copy the current GUI figure to a new figure window. The new figure can be used for further editing and saving to file.

Open this documentation file.

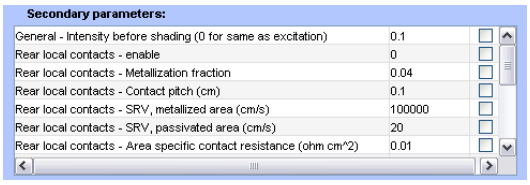
Walkthrough of the different parts of the GUI

The *Parameters* tab



Primary parameters

List of PC1D input parameters, imported from the current .prm file after converting it to ascii text format with the *convert_prm_to_ascii.exe* program. Which parameters that are shown and their names are defined in the text file *parnames.txt* which must be placed in the same folder as the *PC1D for Matlab* program[*]. Values are in units of cm, s, V, etc., if not specified otherwise. Each row have a checkbox that can be checked to indicate a free parameter for optimization and fitting. Sometimes it is useful to link two adjacent parameters together, for instance for simultaneously varying the τ_{n0} and τ_{p0} parameters determining the bulk lifetime. This can be achieved by setting the value of the lowermost parameter to "*same*".
Parameters that are not currently relevant (e.g. coating layer thickness when the "Enable surface coating" value is not enabled) are written in white text to indicate that they will not affect the simulations.



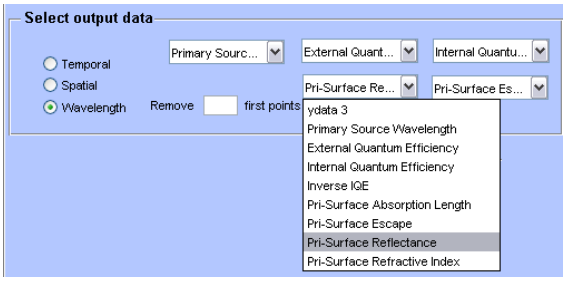
Secondary parameters

Parameters that are used in additional models used to calculate PC1D input parameters. At the time of writing two different models can be enabled, a model for calculating rear SRV and series resistance of a passivated rear surface with local point contacts, and a model for calculating shading and series resistance losses in the front side metallization grid and emitter. (See description below for details.) The parameters can be used in exactly the same way as the normal PC1D parameters, both for parameter variations and fitting. When for instance the model for rear local contacts is enabled the primary PC1D parameters that are affected (S_{0n}, S_{0p} and $R_{s,base}$) are marked in red text).

[*] Some .prm files will generate a longer list of parameters than usual, for instance for simulations including more than one region. The parameter names are then read from a different .txt file indicating the length of the parameter list, e.g. *parnames699.txt.*

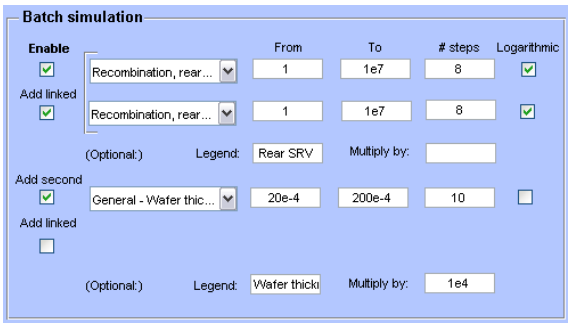
Setup simulation

The *Setup simulation* tab



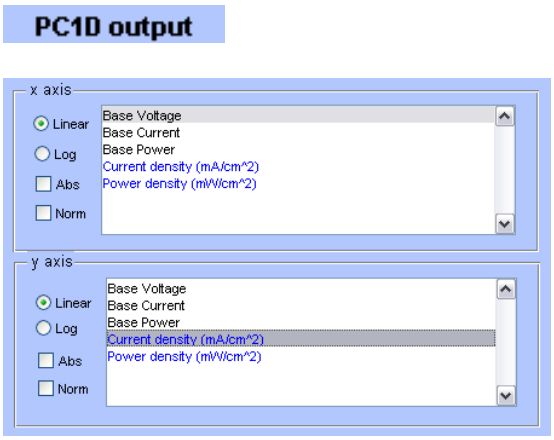
Select output data

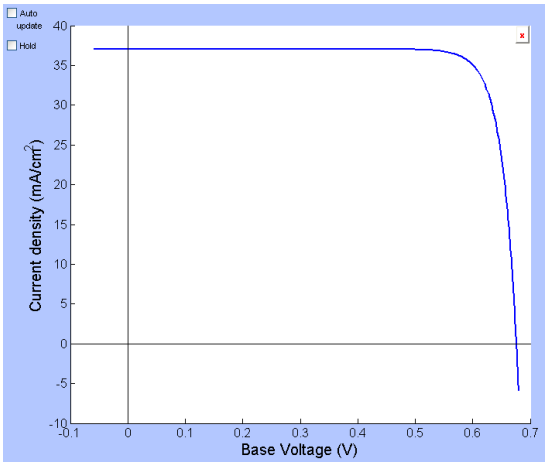
PC1D can be run with one x-data and up to four different y-data as output values. The user can easily change between three different modes: *Temporal,* (typically *Elapsed time* or *Base voltage* as x-data), *Spatial* (typically *Distance from front* as x-data) or *Wavelength* (typically *Primary Source Wavelength* as x-data). When changing between the different modes various standard settings are automatically changed, e.g. like as selecting "*SCAN-QE.EXC*" as excitation in the original PC1D interface. PC1D can also be set to show so-called *Auxiliary* data as output, for instance the electron concentration at a specified depth as a function of elapsed time in a transient simulation. This setting cannot be chosen in the *PC1D for Matlab* interface, but if a .prm file with such output settings is opened, the *Select output data* settings will change accordingly. Calculation of up to four different auxiliary output data sets is then performed by running *cmd-pc1d.exe* several times.



Batch simulation

By clicking the "Enable" checkbox it is possible to setup a parameter variation of one or two parameters in an easy way. The parameters that will be varied can be selected from a list, and the start value, end value and number of steps for each parameter can be specified. By checking the "*Logarithmic*" checkbox the values will be logarithmically spaced. Additional parameters can be added by clicking the appropriate checkboxes, and can be varied either in parallel (linked) or as a second variation, creating a matrix of output data. A custom legend can be added for later plotting. If no legend is chosen, the parameter name from the list will be used. The user may also choose to multiply all values with a constant. This is only for plotting purposes (e.g. to show wafer thicknesses in µm instead of cm) and will not affect the actual simulations.

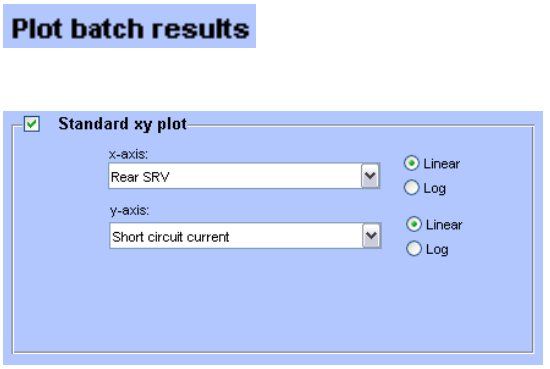


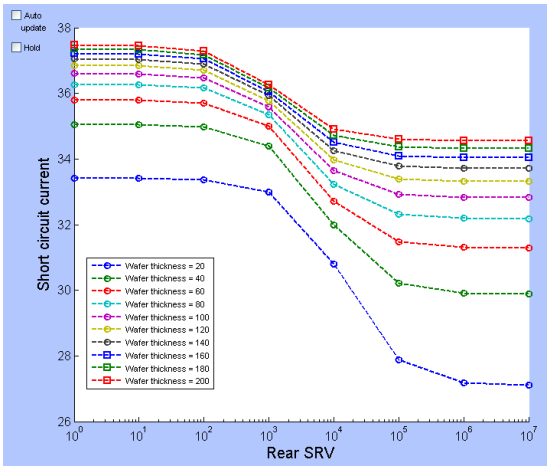


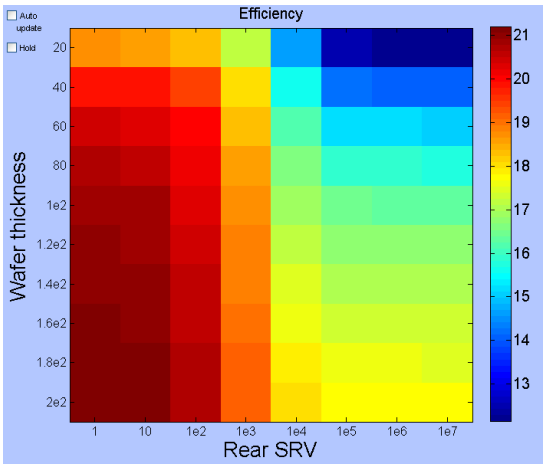
The *PC1D output* tab

Select PC1D output

A list showing the different PC1D output data, with option to select plotting options for the *"Plot output"* button. A single x-data and one or more y-data may be selected. Options for logarithmic plotting and plotting as absolute or normalized values are shown on the left side of the output list. Additional output vectors that are not calculated in PC1D itself, but have been added in the *PC1D for Matlab* program (e.g. Current density) are shown in blue text.







The *Plot batch results* tab

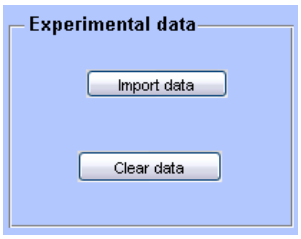
Standard xy-plot

The *PC1D for Matlab* program can calculate different scalar result values based on the PC1D output data (e.g. short circuit current or integrated weighted reflectance). The parameter that have been varied is plotted along the x-axis, and the user can select the corresponding list of calculated result values for plotting along the y-axis. If two parameters have been varied several xy-graphs can be plotted in the same figure. The user can select which parameter to use, and the other will be used as legend. Both linear or logarithmic spacing can be selected for each axis. Finally, the data is plotted using the “Plot results” button.

Plot as 2D color image

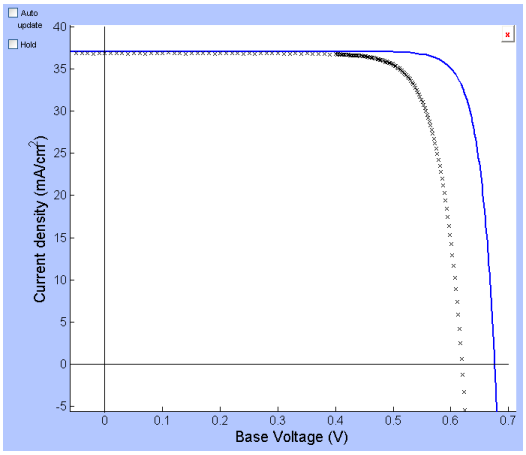
This option can only be used after running a simulation with a variation of two individual parameters. After selecting this option, pressing the “Plot results” button will result in a color image

The *Fit/optimize* tab



Import/clear experimental data

The "Import data" button opens a file selection window, and the selected file is imported into the program an plotted over the existing figure. The file must be in simple ascii text format, containing two data columns without any header lines. The experimental data is shown in the GUI figure window until the "Clear data" button is pressed. When a data file has been imported, the user may fit the current plot to the experimental data by marking one or more fitting checkboxes in the *Parameters* tab and clicking the "Fit" button



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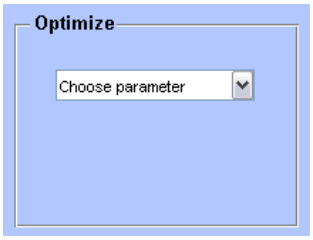
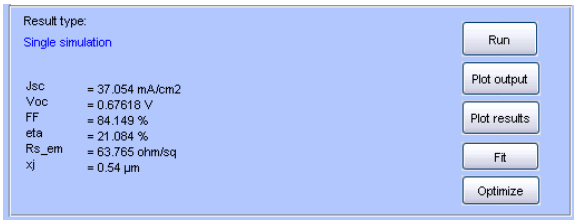


Optimization options

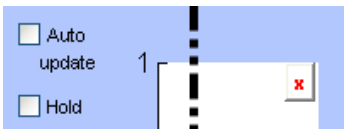
By marking one or more fitting checkboxes in the *Parameters* tab and clicking the "Optimize" button, it is possible to find combination of parameters which maximizes one of the calculated output values. This option is used to select which value that is maximized during the optimization procedure. J_{sc}, V_{oc}, FF and η is currently available, but more options can be added in future updates.

Action buttons and output



This panel is always visible in the bottom part of the GUI. The latest calculated output values are shown on the left hand side, and buttons for starting the most important actions are placed on the right hand side. The "*Run"* button starts a new single simulation or a batch simulation if a parameter variation has been enabled in the "*Setup simulation"* tab. The "*Plot output"* button plots the PC1D output data selected in the "*PC1D output"* tab. If a batch simulation has been performed, all the simulated curves are shown in the same window. The "*Plot results"* button can only be used after a batch simulation, and plots on of the calculated result values as a function of one of the varied parameters (e.g. J_{sc} vs. R_s), or a color image if the "*2D color image"* has been selected. The "Fit" button starts a fitting algorithm used to find the best match to experimental data (see above) and the "Optimize" button uses the free variables (selected in the *Parameters* tab) to maximize the result value selected in the "*Optimization options*" described above.

Additional plot options



By marking the "*Auto update"* checkbox, the *"Plot output"* action will run each time a simulation is performed, and each time a parameter is changed. This can be useful for investigating the effect of varying a parameter, but is not recommended during batch simulations or optimization. (During fitting the output curve will always update regardless of this setting).

By marking the *"Hold"* checkbox, previous plots will not be erased when plotting new data, and a new line color will be used for each new plot.

The red *"x"* at the top right of the figure window can be used to completely clear the figure.

Additional results calculated from PC1D output data – Vector data

Data type		Necessary PC1D output (*cursive*) and parameters (normal)		Calculation details
Current density (mA/cm^2)	J	• *Base Current* • General – Cell area (cm^2)	I A	$J = I/A$
Power density (mW/cm^2)	P_d	• *Base Power* General – Cell area (cm^2)	P A	$P_d = P/A$
AM 1.5G excitation spectrum	S	• *Primary Source Wavelength*		Imported from file AM15G_NREL_ spectral_density.spc
Reflectance times spectrum		• *Primary Source Wavelength* • *Pri-Surface Reflectance*	λ R	$R \times S$
IQE times spectrum		• *Primary Source Wavelength* • *Internal quantum efficiency*	λ IQE	$IQE \times S$
EQE times spectrum		• *Primary Source Wavelength* • *External quantum efficiency*	λ EQE	$EQE \times S$
<u>QSSPC simulation:</u>				
Excess minority carrier density	Δn	• (PC1D output set to auxiliary data) • (Distance from front set to wafer thickness)		$G = G_c/W$ $\sigma = \sigma_c/W$ $\mu_n = f(N_A, N_D, T)$ $\mu_p = f(N_A, N_D, T)$
QSS carrier lifetime	τ_{QSS}	• *Elapsed time* • *Cumulative Photogeneration*	t G_c	$\Delta n = \dfrac{\sigma}{q(\mu_n + \mu_p)}$
Transient carrier lifetime	τ_{tr}	• *Cumulative Excess Conductivity*	σ_c	$\tau_{QSS} = \dfrac{\Delta n}{G}$
Generalized carrier lifetime	τ_{gen}	• General – Wafer thickness • Doping, bulk – Concentration • Doping, bulk – Type • General – Cell temperature	W N_A, N_D T	$\tau_{tr} = -\dfrac{\Delta n}{\dfrac{\mathrm{d}\Delta n}{dt}}$ $\tau_{gen} = \dfrac{\Delta n}{G - \dfrac{\mathrm{d}\Delta n}{dt}}$

Additional results calculated from PC1D output data – Scalar values

Data type		Necessary PC1D output (*cursive*) and parameters (normal)		Calculation details
Short circuit current	J_{sc}			J_{Sc}: J at $V = 0$
Open circuit voltage	V_{oc}			V_{oc}: V at $J = 0$
Fill factor	FF	• *Base Voltage* V • *Base Current* I • General – Cell area (cm^2) A • General – Intensity before shading P_{in}		$P_d = J \times V$ J_{mp}: J at $P_d = \max(P_d)$ V_{mp}: V at $P_d = \max(P_d)$ $FF = \frac{J_{mp} \times V_{mp}}{J_{sc} \times V_{oc}}$
Efficiency	η			$\eta = \frac{\max(P_d)}{P_{in}}$
Junction depth	x_j			x_j: x at $N_A = N_d$
Emitter sheet resistance	$\rho_{\square,em}$	• Front doping enabled		$\mu_n(x) = f(N_A, N_D, T)$ $\mu_p(x) = f(N_A, N_D, T)$ $\sigma(x) = q\mu_n(x)N_D(x) + q\mu_p(x)N_A(x)$ $\rho_{\square,em} = \left(\int_0^{x_j} \sigma(x)dx\right)^{-1}$
Steady state generation rate	G_{ss}			$G_{ss} = G_c/W$
Steady state injection level	Δn_{ss}	• Steady state excitation mode • *Distance from front* x • *Cumulative Photogeneration* G_c • *Excess electron density* Δn_x • General – Wafer thickness W		$\Delta n_{ss} =$ mean (Δn_x) (Excluding near surface regions)
Steady state carrier lifetime	τ_{ss}			$\tau_{ss} = \frac{\Delta n_{ss}}{G_{ss}}$

Sinton optical constant	OC	• Steady state excitation mode • *Cumulative Photogeneration* • General – Wafer thickness • Excitation – Intensity steady state	G_c W P_{ss}	$G = G_c/W$ $OC = 2.7551e19 \times G/P_{ss}$
Generalized lifetime at $\Delta n = 10^{15}$ cm^{-3}	$\tau_{gen,1e15}$	• QSSPC simulation (see previous table)		$\tau_{gen,1e15}$: τ_{gen} *at* $\Delta n = 10^{15}$ *cm^{-3}*
Integrated weighted reflectance	R_{tot}	• *Primary Source Wavelength* • *Pri-Surface Reflectance* • AM 1.5G excitation spectrum	λ R S	Spectrum S imported from file (see above) $R_{tot} = \frac{\int_{\lambda_{\min}}^{\lambda_{max}} R \times S \, d\lambda}{\int_{\lambda_{\min}}^{\lambda_{max}} S \, d\lambda}$

Models used to determine PC1D input parameters

At the time of writing, the *PC1D for Matlab* have included two additional models that are used to further parameterize some of the PC1D input parameters. These calculations can easily be enabled or disabled in the "*Secondary parameters"* list shown in the first tab in the GUI. When the models are enabled, the affected primary parameters are marked with red text.

Secondary parameters	**Used to determine:**
Front side metallization grid:	
Contact finger spacing Contact finger width Contact finger thickness Contact finger length Busbar width Busbar thickness Busbar length Metal resistivity Area specific contact resistance	Excitation – Intensity transient from (mW/cm2) Excitation – Intensity transient to (mW/cm2) Circuit – Emitter Rs (ohm)
Local rear contacts:	
SRV of metallized area SRV of passivated area Metallization fraction Contact pitch Area specific contact resistance	Recombination, rear – SRV parameter for electrons (cm/s) Recombination, rear – SRV parameter for holes (cm/s) Circuit – Base Rs (ohm)

Rear SRV and series resistance in a solar cell with rear local point contacts

The effective rear side surface recombination velocity (SRV) of a passivated Si solar cell with local point contacts can be calculated using Fischer's equation, giving the rear side SRV as [2]

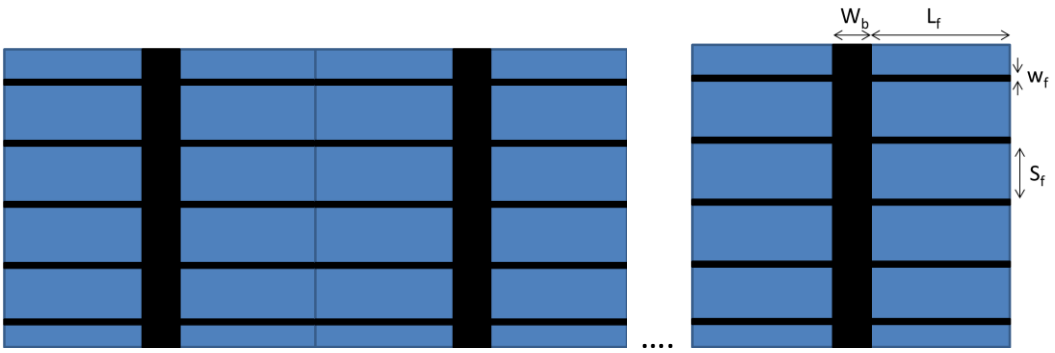
$$S_{eff} = \frac{D}{W}\left(\frac{p}{2W\sqrt{\pi f}}\,arctan\left(\frac{2W}{p}\sqrt{\frac{\pi}{f}}\right) - e^{-\frac{W}{p}} + \frac{D}{fWS_{met}}\right)^{-1} + \frac{S_{pass}}{1-f}$$

where *D* is the minority carrier diffusion constant, *W* is the wafer thickness, *p* is the pitch between the contacts, f is the metallization fraction and S_{met} and S_{pass} are the SRVs of the metallized and passivated regions, respectively. p, f, S_{met} and S_{pass} are included as *secondary parameters* shown in a separate list in the GUI , and can be edited and used for parameter variations and fitting in the same way as the normal PC1D parameters. The calculated value for S_{eff} in the expression above is used to set values for *"Recombination, rear - SRV parameter for electrons"* and *"Recombination, rear - SRV parameter for holes"* in the list of Primary parameters. The GUI also allows for setting a value for the specific contact resistance R_c , which together with the metallization fraction f and the cell area A is used to determine the total internal series resistance of the base contact as:

$$R_{s,base} = \frac{R_c}{A \times f}$$

Front side shading and series resistance losses

To include the effect of shading and series resistance from a front side contact grid, a simple model described in Ref. [3] has also been implemented. If the metallization grid can be described by copying a unit cell in the following manner,



the shading fraction of the contacts $f_{shading}$ can be described as:

$$f_{shading} = \frac{w_f}{S_f} + \frac{w_b}{2L_f + w_b}$$

where w_f is the finger width, S_f is the finger spacing, w_b is the busbar width and L_f is the finger length (these equations assumes a square cell). The illumination intensity is then calculated as

$$P_{excitation} = (1 - f_{shading})P_{in}$$

and used to set the *"Excitation - Intensity transient from"* and *"Excitation - Intensity transient to"* parameters in the list of Primary parameters.
The front side series resistance $R_{s,front}$ (in ohm) can be described as a sum of different contributions (resistance losses in the busbar have been neglected):

$$R_{s,front} = R_{s,fingers} + R_{s,contact} + R_{s,emitter}$$

$$R_{s_{front}} = \frac{1}{A}\left(\frac{\rho_m S_f L_f^2}{3 d_f w_f} + \frac{\rho_c S_f}{w_f} + \frac{\rho_{\square,em} {S_f}^2}{12}\right).$$

Here ρ_m is the metal resistivity, L_f is the finger length, d_f is the finger thickness, ρ_c is the area-specific contact resistance of the fingers, and $\rho_{\square,em}$ is the emitter sheet resistance. The calculated value for $R_{s,front}$ is used to set the *"Circuit - Emitter Rs"* in the list of Primary parameters.

References

[1] H. Haug, B. R. Olaisen, Ø. Nordseth, and E. S. Marstein, "A graphical user interface for multivariable analysis of silicon solar cells using scripted PC1D simulations," in *3rd International Conference for Crystalline Silicon Photovoltaics*, 2013.

[2] B. Fischer, "Loss analysis of crystalline silicon solar cells using photoconductance and quantum efficiency measurements.," Universitaät Konstanz, Konstanz, 2003.

[3] M. A. Green, *Solar cells - Operating principles, technology and system applications*. The university of New South Wales, 1982.