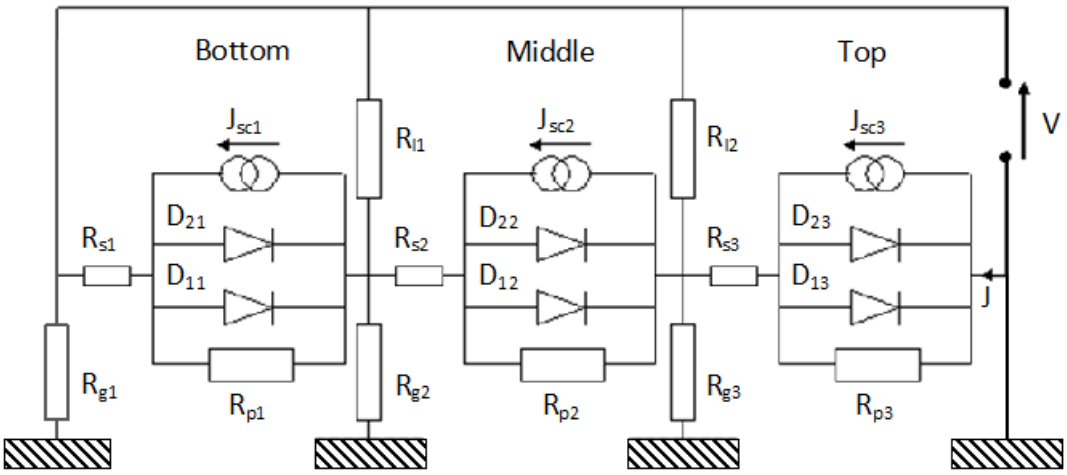
Help Triple-Junction

Triple-Junction

The Triple-Junction program allows a complete study of a device made of up to three junctions modeled as below:



To the usual parameters used to defined a junction (series and parallel resistances, short circuit current source and two diodes) we have added leakage resistances either toward the 'high voltage' point (R_{l1}, R_{l2}) or toward the ground (R_{g1}, R_{g2}, R_{g3}).Taking account of these leakage resistances, for each junction, the program solves the following equation

$$J = J_{sc} - J_{sd1} * \left[Exp\left(\frac{V + R_s J}{m_1 k_b T}\right) - 1\right] - J_{sd2} * \left[Exp\left(\frac{V + R_s J}{m_2 k_b T}\right) - 1\right] - \left(\frac{V + R_s J}{R_p}\right)$$

in which J_{sdi} and m_i are the saturation current and ideality factor for each diode *i*, respectively, k_b is the Boltzmann constant and *T* the temperature, taken equal to 300 K.
This study can be done :

- Loading parameters from **files** already created,
- Entering the parameters values directly in the **Data** window.

The calculation is performed with two or three junctions. The standard configuration is for a triple-junction device but one can work with a tandem device taking J_{sci}, R_{pi} and R_{si} equal to 0 for the diode *i* in the **Data** window.
Once the calculations are done, the *J*(*V*) curves for the complete device or for each junction, or the External Quantum Efficiency (EQE) contribution of each junction, are displayed and can be recorded into files for further work.

Main window

On opening, the **Main** window displays a **Data** window and different menus : **Files**, **Calculations** and **EQE**, EQE for External Quantum Efficiency.
The **Data** window displays the parameters of each junction, parameters that will be used during calculations.
With the **Files** menu one can **Open**, **Save** and **Delete** a Data file. Note that the option **Delete** erases all the files (data and calculated ones) linked to a Data file.
The **Calculations** menu proposes different options of calculation of the ***J***(***V***) curves of the device depending on the conditions under which the device is set. For instance, the **Independent** option calculates the *J*(*V*) curves of each of the three junctions taken alone under dark and under illumination. It plays the same role as the **Calculation** button found in the **Data** window.
The **EQE** menu proposes also different options to evaluate the **EQE** contribution of each junction depending on the conditions under which the complete device is studied.
After calculations, the *J*(*V*) or the EQE curves are displayed in the **Main** window and can be saved for further treatment.

Data window

The data window displays a scheme of one junction (on the left). A set of parameters for each junction - series (R_s) and parallel (R_p) resistances, short circuit current densities (J_{sc}), etc...- is proposed which may not corresponds to the expected one. These parameters can be modified to match the expected values. The unit of the J_{sc} is A/cm^2 and, for homogeneity, the unit of the 'resistances' is Ω.cm^2. For each junction the set of parameters is displayed with a different color depending on its position in the device : blue, green and red for the top (#3), middle (#2) and bottom (#1) junction, respectively.
In addition to the set of parameters for each junction, values for the leakage resistances are proposed. These values are taken very large but can be modified by the user.
A generic name under which the curves will be saved is proposed (e.g. *Myfile*). This name can be modified when recording the data into a Data file. On opening the generic name is *Test*.
Finally, a button **Calculation** is displayed. A left click on this button starts the calculation of the ***J***(***V***) curves of each junction taken alone under dark and under illumination. These curves are subsequently displayed in the **Main** window.

J(V) & EQE curves

After calculation, the *J*(*V*) or the EQE curves are displayed in the **Main** window. Depending on the conditions under which the calculation is done different plots will be shown.
For the *J*(*V*) curves when calculated either for each junction independently or considering the complete device in whole (all junctions under dark or illuminated), two plots are given : a linear-log plot for the junctions under dark and a linear-linear plot for the junctions under illumination.
When all the junctions are not under the same conditions (some illuminated and the other(s) under dark) only a linear-linear *J*(*V*) plot is proposed.
For the EQE curves only a linear-linear plot (%EQE vs *V*) is displayed.

When the device can be considered in its whole, the colors of the plots are dark orange (dark conditions) or bright orange (Illuminated condition) otherwise the color used to display the contribution of one junction will match that of the **Data** window, dark if the junction is under dark or bright if the junction is illuminated.

Files

Data files are saved in the working directory with an extension **.trj**.

* To open a data file, left click on **Files** then on **Open** or use the shortcut CTRL-O. A window opens showing the working directory displaying the data files saved in it. Choose one and left click on 'Open' or double left click on the file name. The data of the **Data** window is automatically modified according to the data of the file.

* To record a data file, left click on **Files** then on **Save** or use the shortcut CTRL-S. A window opens showing the working directory and the data files already saved. Give a name to the file and left click on 'Save'. It is not necessary to add the extension **.trj** that will be automatically added. To record a data file already saved, after some modifications, give the same name to the file or double left click on the displayed name of the file. A message is displayed indicating that the data file already exists. Left click on **Yes** to go on. To cancel recording left click on **No**.

* To delete a data file left click on **Files** then on **Delete**. A window opens showing the working directory displaying the data files saved in it. Choose one and left click on 'Open' or double left click on the file name. A message appears warning that ALL the files related to this data file will be deleted. Left click on **Yes** to proceed or on **No** to stop deleting.

* To quit the program left click on **Quit** or use the shortcut CTRL-Q. A confirmation message is displayed. Left click on **Yes** to quit or on **No** to go back to the program.

The data of a file are saved under ASCII and can be read with Notepad from Windows®. The file is organized as follow :

- R_{si} = value of the series resistance of junction *i*
- R_{pi} = value of the parallel resistance of junction *i*
- J_{cci} = value of the current density of junction *i*
- I_{sdi1} = value of the saturation current of diode 1 of junction *i*
- I_{sdi2} = value of the saturation current of diode 2 of junction *i*
- m_{i1} = ideality coefficient of diode 1 of junction *i*
- m_{i2} = ideality coefficient of diode 2 of junction *i*

starting from junction #1 to junction #3, followed by

- R_{l1} = value of the leakage resistance R_{l1}
- R_{l2} = value of the leakage resistance R_{l2}
- R_{g1} = value of the leakage resistance R_{g1}
- R_{g2} = value of the leakage resistance R_{g2}
- R_{g3} = value of the leakage resistance R_{g3}

Calculation files

Due to the very large number of files that can be generated during a complete study they are saved in a directory *Myfile*_trj of the working directory, *Myfile* being the generic name

defined in the **Data** window. Different types of files resulting from the calculation can be saved. The extension of these files will depend on the type of calculation from which they are issued and determined by the chosen menu option.

* **Calculations\Independent**

This option calculate the *J*(*V*) curves of each junction taken alone, both under illumination and under dark. The files are saved as *Myfile*_J(V)_#i.txt and *Myfile*_J(V)_#i_dark.txt, *Myfile* being the generic name defined in the **Data** window, *i* the number of the junction (3 for the Top, 2 for the Middle and 1 for the Bottom) and *dark* indicating that the calculation was done with the junction under dark. The files are made of two columns : the first one containing the *V* values and the second one containing the *J* values. Note that with this option, if one chooses to save the calculation results, the file *Myfile*.trj is saved again with the data used to perform the calculation. It is also the case when using the **Calculation** button of the **Data** window.

* **Calculations\All Junctions**

This option calculates the *J*(*V*) curves when all the junctions of the device are under illumination and under dark, taking account, or not, of the leakage resistances. The files are saved as *Myfile*_J(V)_AllJunctions.txt and *Myfile*_J(V)_AllJunctions_dark.txt, without leakage resistances (Option **Without Rl**), and as *Myfile*_J(V)_AllJunctions_Rl.txt and *Myfile*_J(V)_AllJunctions_dark_Rl.txt (Option **With Rl + Rg**), with leakage resistances, *Myfile* being the generic name defined in the **Data** window. The files are made of five columns : the first one containing the *V* values, the second one containing the *J* values and the last three columns the values of the voltages for junction 3 (top), 2 (middle) and 1 (bottom), respectively.

* **Calculations\2 Junctions**

This option calculates the *J*(*V*) curves when 2 junctions of the device are under illumination and the third one is under dark, taking account, or not, of the leakage resistances. This option is not available when dealing with a tandem cell. Without leakage resistances (Option **Without Rl**), the files are saved as *Myfile*_J(V)_2Junctions_#i&#j.txt, where *i* and *j* are the indices of the illuminated junctions, *Myfile* being the generic name defined in the **Data** window. With leakage resistances (Option **With Rl + Rg**), the files are saved as *Myfile*_J(V)_2Junctions_#i&#j_Rl.txt. The files are made of five columns : the first one containing the *V* values, the second one containing the *J* values and the last three columns the values of the voltages for junction 3 (top), 2 (middle) and 1 (bottom), respectively.

* **Calculations\1 Junction**

This option calculates the *J*(*V*) curves when 2 junctions of the device are under dark and the third one is under illumination, taking account, or not, of the leakage resistances. Without leakage resistances (Option **Without Rl**), the files are saved as *Myfile*_J(V)_1Junction_#i.txt, where *i* is the index of the illuminated junction, *Myfile* being the generic name defined in the **Data** window. With leakage resistances (Option **With Rl + Rg**), the files are saved as *Myfile*_J(V)_1Junction_#i_Rl.txt. The files are made of five columns : the first one containing the *V* values, the second one containing the *J* values and the last three columns the values of the voltages for junction 3 (top), 2 (middle) and 1 (bottom), respectively.

EQE Files

Due to the very large number of files that can be generated during a complete study they are saved in a directory *Myfile*_trj of the working directory, *Myfile* being the generic name

defined in the **Data** window. Different files resulting from the calculation of the EQE contribution can be saved. The extension of these files will depend on the type of calculation from which they are issued and determined by the chosen menu option.

* **EQE\All junctions**

This option calculates the EQE contribution of the junctions the device being illuminated (Sub option **Illuminated**) or under dark (Sub option **Dark**). The files are saved as *Myfile*_EQE.txt and *Myfile*_EQE_dark.txt, *Myfile* being the generic name defined in the **Data** window. The files are made of five columns : the first one containing the *V* values, the second one containing the *J* values of the device under illumination or under dark, and the last 3 columns the percentages of contribution of each junction to the current during EQE 'measurements'. The values are set to 0 when the percentage was not calculated.

The second option depends on the considered device. Dealing with a triple junction this option is **2 junctions** with three sub options:

* **2 junctions\1 and 2 illuminated**
* **2 junctions\1 and 3 illuminated**
* **2 junctions\2 and 3 illuminated**

The files are saved as *Myfile*_EQE_2Junc_#i&#j_ill.txt, where *i* and *j* are the indices of the junctions under illumination, *Myfile* being the generic name defined in the **Data** window. The files are made of five columns : the first one containing the *V* values, the second one containing the *J* values of the device with the 2 junctions under illumination, and the last 3 columns the percentages of contribution of each junction to the current during EQE 'measurements'. The values are set to 0 when the percentage was not calculated.

If the device under study is a tandem cell, the other option is **1 junction** with two sub options concerning the junctions that have been selected to be part of the tandem cell. Each option consists in one junction under illumination and the other under dark. The files are saved as *Myfile*_EQE_1Junc_#i_ill.txt, where i is the index of the junction under illumination, *Myfile* being the generic name defined in the **Data** window. The files are made of five columns : the first one containing the *V* values, the second one containing the *J* values of the device with the junction under illumination, and the last 3 columns the percentages of contribution of each junction to the current during EQE 'measurements'. The values are set to 0 when the percentage was not calculated.

Calculations

The calculations are performed by solving the equation

$$J = J_{sc} - J_{sd1} * \left[Exp\left(\frac{V + R_s J}{m_1 k_b T}\right) - 1\right] - J_{sd2} * \left[Exp\left(\frac{V + R_s J}{m_2 k_b T}\right) - 1\right] - \left(\frac{V + R_s J}{R_p}\right)$$

in which J_{sdi} and m_i are the saturation current and ideality factor for each diode *i*, respectively, k_b is the Boltzmann constant and *T* the temperature, taken equal to 300 K.

The leakage resistances can be taken, or not, into account during the calculation. Different types of calculations can be performed for a given device depending on the junctions 'experimental' conditions. These 'experimental' conditions can be chosen in the **Calculations** menu.

* **Calculations\Independent**

This option calculate the *J*(*V*) curves of each junction taken alone, both under illumination and under dark. The resulting curves are displayed in the **Main** window. The colors chosen for the displayed curves are those of the junction data displayed in the **Data** window. Dark blue, green and red for the top (#3), middle (#2) and bottom (#1), respectively, in a linear-log plot when the junction is under dark, and bright blue, green and red for the top (#3), middle (#2) and bottom (#1), respectively, in a linear-linear plot when the junction is under illumination.

* **Calculations\All Junctions**

This option calculates the *J*(*V*) curves when all the junctions of the device are under illumination and under dark, taking account (Option **With Rl + Rg**), or not (Option **Without Rl**), of the leakage resistances. The colors chosen for the displayed curves in the **Main** window are dark orange in a linear-log plot when the device is under dark and bright orange in linear-linear plot when the device is under illumination.

* **Calculations\2 Junctions**

This option calculates the *J*(*V*) curves when 2 junctions of the device are under illumination and the third one is under dark, taking account (Option **With Rl + Rg**), or not (Option **Without Rl**), of the leakage resistances. This option is not available when dealing with a tandem cell. The curves are displayed in the **Main** window in a linear-linear plot with the color of the junction under *dark*.

* **Calculations\1 Junction**

This option calculates the *J*(*V*) curves when 2 junctions of the device are under dark and the third one is under illumination, taking account, or not, of the leakage resistances. The curves are displayed in the **Main** window in a linear-linear plot with the color of the junction under *illumination*.

The displayed curves can be saved into an image with a double left click onto them. These images are saved under the **.bmp** format in the directory *Myfile*_trj. The size of these files can be reduced by pasting them in Paint from Windows® and, subsequently, saving them in a **.png** format.

EQE

This menu allows the study of the contribution of the junctions of the device to the External Quantum Efficiency (EQE). The program calculates the respective response of each junction when they are all illuminated and an extra illumination, as in an EQE measurement experiment, is added that would generates a ΔJ_{cc0} of 0.1 mA/cm^2 in each of them taken alone. The results are calculated in percentage of the ΔJ_i measured in the complete device when the i^{th} junction generates a current due to the extra illumination compared to the ΔJ_{icc0} of the corresponding junction taken alone and *under illumination*. It is a way to investigate on the 'artifacts' that may appear during EQE measurement at a junction which is assumed to present no response during measurement due to the saturation provided by the illumination [**References**].

If leakage resistances are present the calculation is performed taking account of them. Different options of calculations are available.

* **All junctions\Illuminated**

The percentages of contribution to the EQE as function of the applied voltage of each junction are displayed in the **Main** window with the color of the junction: bright blue, green and red for the top (#3), middle (#2) and bottom (#1), respectively.

* **All junctions\Dark**

The percentages of contribution to the EQE as function of the applied voltage of each junction are displayed in the color of the junction: dark blue, green and red for the top (#3), middle (#2) and bottom (#1), respectively.

If the device under study is a triple-junction, the other option is **2 junctions** with three sub options:

* **2 junctions\1 and 2 illuminated**

The percentages of contribution to the EQE as function of the applied voltage of each junction are displayed in the color of the junction: bright blue, bright green and dark red for the top (#3), middle (#2) and bottom (#1), respectively.

* **2 junctions\1 and 3 illuminated**

The percentages of contribution to the EQE as function of the applied voltage of each junction are displayed in the color of the junction: bright blue, dark green and bright red for the top (#3), middle (#2) and bottom (#1), respectively.

* **2 junctions\2 and 3 illuminated**

The percentages of contribution to the EQE as function of the applied voltage of each junction are displayed in the color of the junction: dark blue, bright green and bright red for the top (#3), middle (#2) and bottom (#1), respectively.

If the device under study is a tandem cell, the other option is **1 junction** with two sub options concerning the junctions that have been selected to be part of the tandem cell. Each option consists in one junction under illumination and the other under dark. The curves are displayed in their respective color, dark for the one under dark and bright for the one under illumination.

The displayed curves can be saved into an image with a double left click onto them. These images are saved under the **.bmp** format in the directory *Myfile*_trj. The size of these files can be reduced by pasting them in Paint from Windows® and, subsequently, saving them in a **.png** format.

References

M. Meusel, C. Baur, G. Létay, A. W. Bett, W. Warta and E. Fernandez, *Prog. Photovolt: Res. Appl.* 2003; **11**: 499-514.