

# ReRa Tracer Manual

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## WELCOME

In Tracer you have found your all-in-one solution for the measurement and analysis of IV-curve measurements. Tracer is the core application developed by ReRa that will help you to characterize your solar cells and compare the results.

This manual will help you to use Tracer. It will explain the workflow to follow and how to setup a high quality measurement protocol for your solar cells. For more information please contact Abet-Technologies:

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## RERA TRACER

### introduction

The characterization of solar cells is necessary to improve and monitor the quality of solar cells. Different characterization techniques exist, but the most common one is, without doubt, the IV-curve measurement. By tracing the IV curve of a solar cell, the most important parameters describing the solar cell behavior can be determined. ReRa Tracer will help you measure the IV curves and analyze the data by means of different calculation techniques. A short overview of solar cell theory will be given before the focus will be on the application.

## SOLAR CELL THEORY

### Simple explanation

- Photons in sunlight hit the solar cell and are absorbed by semiconducting materials, such as silicon.
- Electrons (negatively charged) are separated from their atoms, allowing them to flow through the material to produce electricity.
- The complementary positive charges that are also created are called holes and flow in the direction opposite of the electrons in a solar cell.

### Photogeneration of charge carriers

When a photon hits a piece of solar cell material, one of three things can happen:

- The photon can pass straight through the solar cell material this (generally) happens for lower energy photons
- The photon can reflect off the surface

- The photon can be absorbed by the solar cell material, if the photon energy is higher than the band gap value. This generates an electron-hole pair and sometimes heat, depending on the band structure.

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually this electron is in the valence band, and is tightly bound in covalent bonds between neighboring atoms, and hence unable to move far. The energy given to it by the photon "excites" it into the conduction band, where it is free to move around within the semiconductor. The covalent bond that the electron was previously a part of now has one fewer electron this is known as a hole. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to move into the "hole," leaving another hole behind, and in this way a hole can move through the lattice. Thus, it can be said that photons absorbed in the semiconductor create mobile electron-hole pairs.

### Charge carrier separation

There are two main modes for charge carrier separation in a solar cell:

- Drift of carriers, driven by an electrostatic field established across the device
- Diffusion of carriers from zones of high carrier concentration to zones of low carrier concentration (following a gradient of electrochemical potential).

In the widely used p-n junction solar cells, the dominant mode of charge carrier separation is by drift. However, in non-p-n-junction solar cells (typical of the third generation of solar cell research such as dye and polymer thin-film solar cells), a general electrostatic field has been confirmed to be absent, and the dominant mode of separation is via charge carrier diffusion.

### The p-n junction

The most commonly known solar cell is configured as a large-area p-n junction made from silicon. As a simplification, one can imagine bringing a layer of n-type silicon into direct contact with a layer of p-type silicon. In practice, p-n junctions of silicon solar cells are not made in this way, but rather, by diffusing an n-type dopant into one side of a p-type wafer (or vice versa).

If a piece of p-type silicon is placed in intimate contact with a piece of n-type silicon, then a diffusion of electrons occurs from the region of high electron concentration (the n-type side of the junction) into the region of low electron concentration (p-type side of the junction). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. The diffusion of carriers does not happen indefinitely however, because of an electric field which is created by the imbalance of charge immediately on either side of the junction which this diffusion creates. The electric field established across the p-n junction creates a diode that promotes current to flow in only one direction across the junction. Electrons may pass from the n-type side into the p-type side, and holes may pass from the p-type side to the n-type side, but not the other way around. This region where electrons have diffused across the junction is called the depletion region because it no longer contains any mobile charge carriers. It is also known as the "space charge region".

### Connection to an external load

Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes connected to an external load. Electrons that are created on the n-type side, or have been "collected" by the junction and swept onto the n-type side, may travel through the wire, power the load, and continue through the wire until they reach the p-type semiconductor-metal contact. Here, they recombine with a hole that was either created as an electron-hole pair on the p-type side of the solar cell, or swept across the junction from the n-type side after being created there.

## SOLAR CELL PARAMETERS

### Equivalent circuit of a solar cell

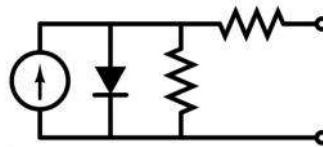
To understand the electronic behavior of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete electrical components whose behavior is well known. An ideal solar cell may be modeled by a current source in parallel with a diode:

$$I = I_0 \left( \exp \left( \frac{q}{nKT} V \right) - 1 \right) - I_{sc}$$

in practice no solar cell is ideal, and a shunt resistance and a series resistance component are added to the model. This results in the so called 'single diode model'

$$I = I_0 \left( \exp \left( \frac{q}{nKT} (V - IR_s) \right) - 1 \right) - I_{sc}$$

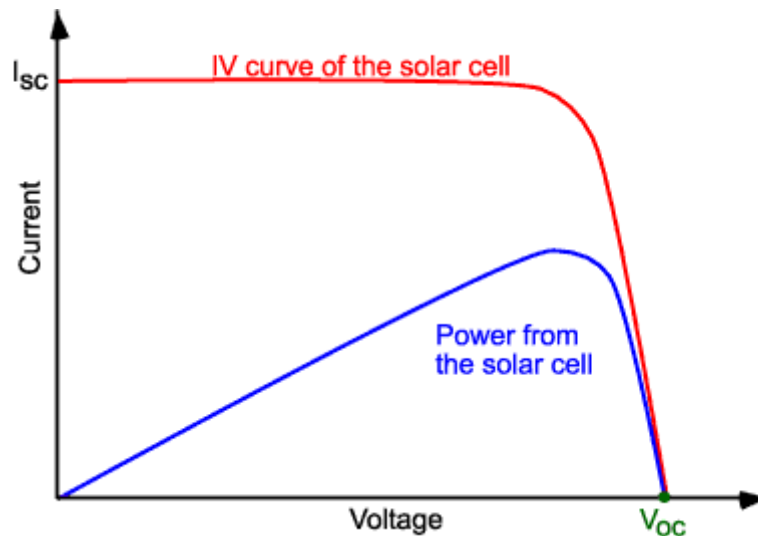
The electronic equivalent can be drawn as follows:



For some cells the solar cell behavior is better described by adding a second diode in parallel, which results in the double diode model.

### IV-curve

Measuring the IV curve of a solar cell is done by illuminating the solar cell and changing the load that is connected to the device. By measuring the voltage and current pairs at different loads the so called IV-curve is traced. This curve shows the important parameters of the solar cell.



### Energy conversion efficiency

A solar cell's energy conversion efficiency ( $\eta$ , "eta"), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of the maximum power point,  $P_{mpp}$ , divided by the input light irradiance ( $E$ , in  $W/m^2$ ) under Standard Test Conditions (STC) and the surface area of the solar cell ( $A$  in  $cm^2$ ).

STC specifies a temperature of  $25^\circ C$  and an irradiance of  $1000 W/m^2$  with an airmass 1.5 Global (AM1.5G) spectrum. These correspond to the irradiance and spectrum of sunlight incident on a clear day upon a sun-facing  $37^\circ$ -tilted surface with the sun at an angle of  $42^\circ$  above the horizon. This condition approximately represents solar noon near the spring and autumn equinoxes in the continental United States with surface of the cell aimed directly at the sun. Thus, under these conditions a solar cell of 12% efficiency with a  $100 cm^2$  surface area can be expected to produce approximately 1.2 watts of power.

The losses of a solar cell may be broken down into reflectance losses, thermodynamic efficiency, recombination losses and resistive electrical loss. The overall efficiency is the product of each of these individual losses.

### Short Circuit current

The short circuit current ( $I_{sc}$ ) of a solar cell is defined as the current that flows when the solar cell is short circuited ( $V = 0$ )

### Open Voltage

The open voltage ( $V_{oc}$ ) of a solar cell is defined as the voltage when no current flows ( $I=0$ ).

### Maximum-power point

A solar cell may operate over a wide range of voltages ( $V$ ) and currents ( $I$ ). By increasing the resistive load on an irradiated cell continuously from zero (a short circuit) to a very high value (an open circuit) one can determine the maximum-power point, the point that maximizes  $V \times I$ ; that is, the load for which the cell can deliver maximum electrical power at that level of irradiation. (The output

power is zero in both the short circuit and open circuit extremes).

A high quality, mono crystalline silicon solar cell, at 25 °C cell temperature, may produce 0.60 volts open-circuit (Voc). The cell temperature in full sunlight, even with 25 °C air temperature, will probably be close to 45 °C, reducing the open-circuit voltage to 0.55 volts per cell. The voltage drops modestly, with this type of cell, until the short-circuit current is approached (Isc). Maximum power (with 45 °C cell temperature) is typically produced with 75% to 80% of the open-circuit voltage (0.43 volts in this case) and 90% of the short-circuit current. This output can be up to 70% of the Voc x Isc product. The short-circuit current (Isc) from a cell is nearly proportional to the illumination, while the open-circuit voltage (Voc) may drop only 10% with an 80% drop in illumination. Lower-quality cells have a more rapid drop in voltage with increasing current and could produce only 1/2 Voc at 1/2 Isc. The usable power output could thus drop from 70% of the Voc x Isc product to 50% or even as little as 25%.

### Fill factor

Another defining term in the overall behavior of a solar cell is the fill factor (FF). This is the ratio of the maximum power point divided by the open circuit voltage (Voc) and the short circuit current (Isc):

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} = \frac{I_{mpp} V_{mpp}}{I_{sc} V_{oc}}$$

## SETTING UP THE APPLICATION

### Preparing the PC

ReRa Tracer is most commonly used in combination with one of the Keithley Sourcemeters 24xx. Communication with a Keithley Sourcemeter is done by means of a GPIB connection. Standard computers do not have this interface available; therefore a GPIB interface has to be installed. Tracer supports the NI GPIB-USB-HS interface. This is a high speed interface that only requires a USB 2.0 connection.



GPIB-USB-HS

Install the National Instruments NI488.2 software that comes with the NI GPIB-USB-HS.

The Keithley Sourcemeters can be controlled over serial port or by means of the GPIB connection. Tracer does not support communication over serial link. The factory setting of the Keithley Sourcemeter is GPIB. To be able to control the Keithley Sourcemeter over GPIB, the instrument has to be set in GPIB mode. This

can be done by selecting this from the Communication option in the Main Menu on the front panel of the Keithley Sourcemeter.

### ReRa Tracer Installation

To install ReRa Tracer, the computer needs to have Windows XP (SP2) or higher as operating system. ReRa Tracer is developed for both 32 bit and 64 bit version of Windows. The prerequisites for ReRa Tracer are:

- Microsoft .NET framework 3.5
- SQL Server Compact 3.5
- National Instruments Visa 4.2 (or higher)

The installer will install the first two packages when they are not already available on the system. The National Instruments software has to be installed manually; this is caused by a license requirement. Note that installing these packages will take a long time, from 30-45 minutes!

### Install National Instruments VISA

If there is no National Instruments VISA on the computer, it has to be installed. To check if there is VISA on the computer go to National Instrument Measurement & Automation (if available). Select Software/NI-VISA. The version of VISA should be at least 4.2. To install NI-VISA execute the visa430full.exe installer on the installation medium.

### Run the ReRa Tracer installer

To install ReRa Tracer, execute 'setup.exe' from the installation folder.

### Setting up the Temperature Readout Unit (optional)

ReRa Tracer supports natively the NOVUS myPCLab temperature readout unit. This low-cost device can be obtained from [www.novusautomation.com](http://www.novusautomation.com).



Use the myPCLab installation instructions to install the device. Note that the myPCLab currently does not support 64 bit version of Windows! After installation run the myPCLab application to setup the device. Different kind of temperature sensors can be connected; thermocouples and RTD's. Be sure to check the 'Enable auto-send mode' option in the General Tab, if this is not selected ReRa Tracer will be unable to detect the device.

### Finalizing the installation

ReRa Tracer setup is now completed. You can run ReRa Tracer by double-clicking the icon on the Desktop. On the desktop a folder named Tracer

Extensions is created. You can install these extensions from within the ReRa Tracer application.



RERA TRACER ICON

## RUNNING RERA TRACER

### USB Hardware key

To run ReRa Tracer a valid USB hardware key should be inserted into the computer. The hardware key will install without external drivers.



HARDWARE KEY

### License code

ReRa Tracer will only run when there is a valid license code. This license code will only work with the Hardware key delivered with the application.

### Local database

The first time ReRa Tracer is executed, it will detect that there is no local database available. It will automatically generate this database and the application is ready to be used.

## RERA TRACER WORKFLOW

### Calibrating a solar cell

To start calibrating a solar cell, first of all the solar simulator has to be switched on. Xenon arc sources normally need a long time (30 minutes) to stabilize. Always wait at least this time before starting the measurements. Before the solar cell can be calibrated it is necessary to know the irradiance level of the simulator. Therefore, mount a reference cell and perform an illuminated measurement:

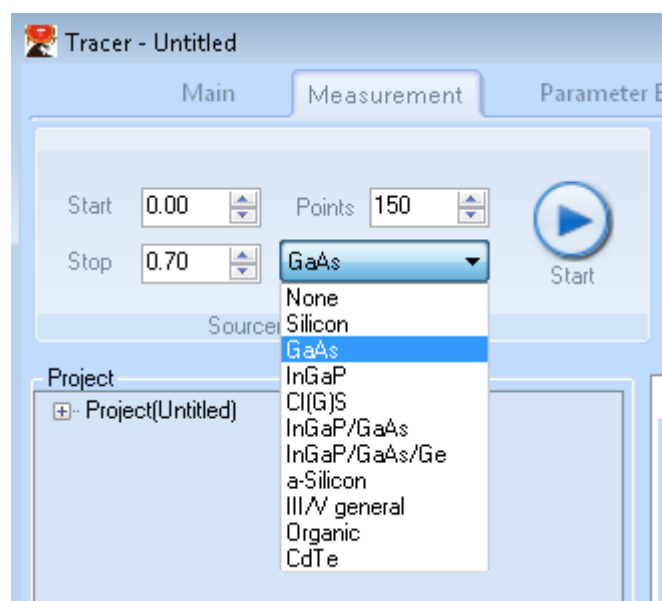
### Illuminated Measurement

Activate the Measurement menu tab.

Set the sweep voltage range according to the material of the solar cell to be measured. Selecting the correct voltage range can be done in three ways:

- 1) Selecting the material from the dropdown menu:





**SELECTING THE MATERIAL WILL SET THE CORRECT VOLTAGE RANGE FOR THE SWEEP**

- 2) Measure the open voltage by clicking 'Measure Voc' which is located on the right of the Start button. After the Voc is measured, double click the voltage value and the sweep stop voltage will be set to the correct value.



**DOUBLE CLICK THE MEASURED VOC TO DETERMIN A VALIF STOP SWEEP VOLTAGE**

- 3) Manually set the Start and Stop values.

Be sure that the shutter control on the solar simulator is set to 'External' and press the Start button. A curve will now be measured.

You will be presented with a device info dialog box.

New or Existing Device

Device to measure

Code: DUT\_1

Suffix: Size [cm2]: 1.0000

Material: GaAs

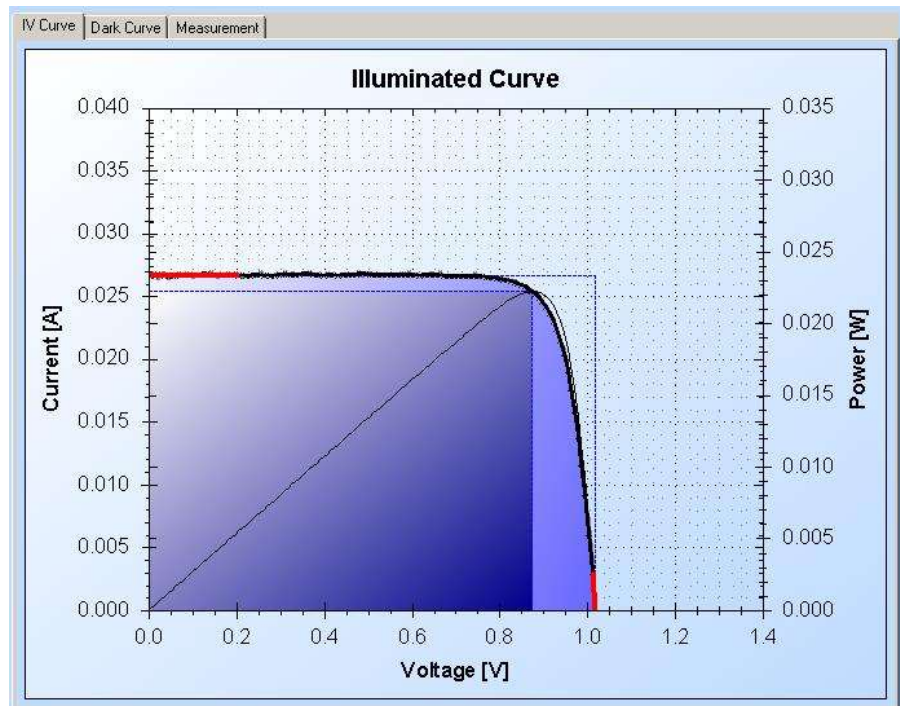
Store measurement automatically in database

Cancel OK

INSERT THE DEVICE DATA

Insert the device code for the solar cell to be measured. By using an underscore followed by a number, Tracer enables auto numbering mode. This means that the next time a device is measured; it will be automatically given the same name with an increased number. A suffix can be added to the device, but keep the suffix as short as possible. After the measurement detailed comments can be added. Select the size. The material is copied from the selection of the sweep voltage materials. If the material is changed in this dialog, it will not affect the sweep voltage range.

Press OK and a curve should appear on screen:



MEASURED ILLUMINATED CURVE OF A GAAS REFERENCE SOLAR CELL

This measurement will now be used to set the simulator irradiance. Press the Irradiance button and select the reference cell used.



IRRADIANCE BUTTON

If the data of the used reference cell is not available, it has to be inserted it by using the *Options/Reference* menu (See section Reference Cells). Once the reference cell is selected the irradiance is set. The set irradiance can be seen at the left bottom corner of the main screen.

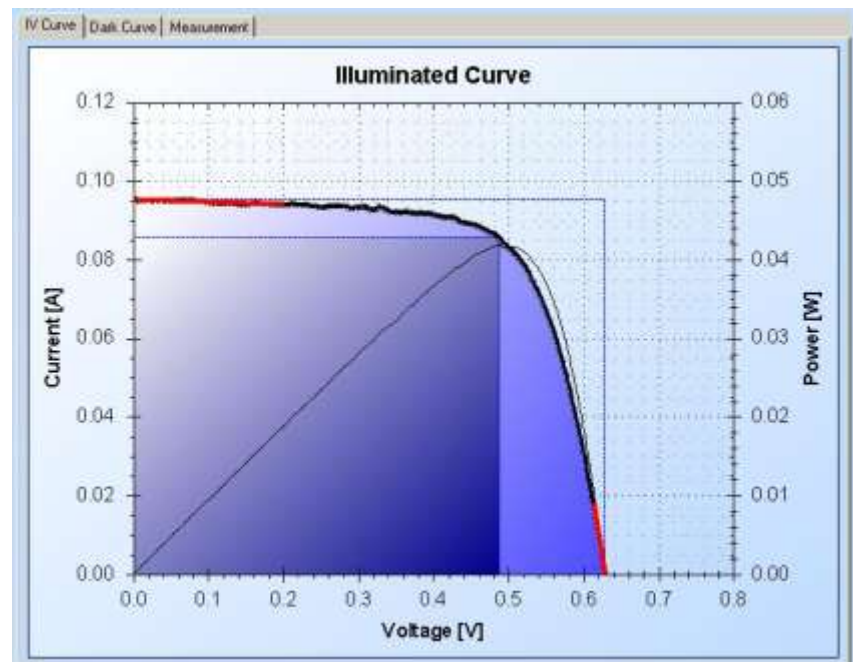
The IrradianceDialog dialog box contains the following fields and controls:

- Available Reference Cells:** A dropdown menu showing 'R2979C'.
- Measured Isc:** A text field displaying '26.66 mA'.
- Simulator Irradiance:** A text field displaying '1035 W/m<sup>2</sup>'.
- Buttons:** 'OK' and 'Cancel' buttons at the bottom.

SELECT REFERENCE USED

In this example the measured short circuit current was 26.66 mA. The calibration value of the cell is 25.77 mA @ 1000 Wm<sup>-2</sup> AM1.5G. Therefore the simulator irradiance (for the reference material type) is:  $1000 * 26.66 / 25.77 = 1035$  Wm<sup>-2</sup>.

Remove the reference cell. Mount the solar cell that needs to be calibrated at approximately the same position as the reference cell. Having a uniform light distribution is one of the most difficult parameters for solar simulators. To be sure to have the least influence of non-uniformity, always mount the solar cells at approximately the same position. Use the same procedure again to measure the illuminated curve of the solar cell.

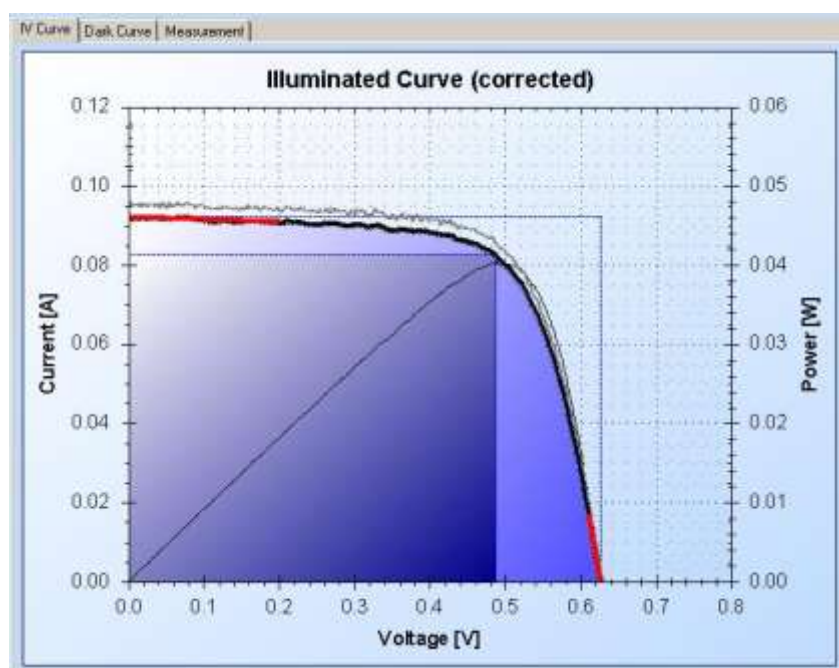


MEASURED SILICON CELL

The cell is now measured however it is not corrected to standard test conditions (STC). To do this press the correct to STC radio button at the *Parameter Extraction* menu.



The curve is now corrected to 1000Wm<sup>-2</sup> and 25°C, the original curve is shown in gray.



MEASUREMENT CORRECTED TO STC

Save the project.

## DATABASE

### Local database

ReRa Tracer is installed with its own database. The database is required for the operation of the software, but it can also be used for storage of the curves measured. The maximum size of the local database is 4Gb. Storing and retrieving curves from the database is done by the two buttons on the Measurement menu.



If a curve is selected, pressing the 'Store' button will store the curve to the local database. The curve can be retrieved by pressing the 'Load' button.

### External databases

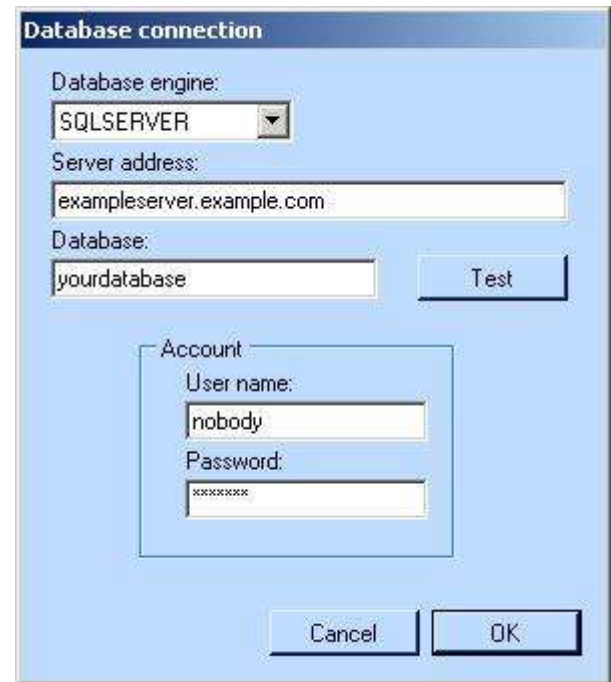
If it is required to store the curves into another database, then ReRa Tracer supports two external databases: MySQL and Microsoft SQL Server. ReRa Tracer can store curves into these databases, however it is not possible to retrieve the curves from these databases.

### SQL Server

To setup a SQL Server database for curve storage, ask you database

administrator to setup a new database by using the required SQL-script that can be downloaded from the ReRa server.

You will need the following data from your database administrator to use the database: Server address, Database name, User name, Password. If you have this information you can setup ReRa Tracer to use the external SQL Server database by selecting the 'Database' item on the 'Options' menu (see picture)



SETTING UP THE SQL SERVER DATABASE

## MySQL

To setup a MySQL database for curve storage, ask you database administrator to setup a new database by using the required SQL-script that can be downloaded from the ReRa server.

You will need the following data from your database administrator to use the database: Server address, Database name, User name, Password. If you have this information you can setup ReRa Tracer to use the external SQL Server database by selecting the 'Database' item on the 'Options' menu (see picture)

SETTING UP THE MYSQL DATABASE

## REFERENCE CELLS

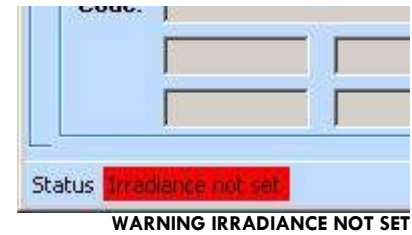
The irradiance level of the solar simulator is determined by a reference cell. Be sure to have a reference cell that has a spectral response similar to the cell to be tested. If this is the case a mismatch in the simulator spectrum does not really influence the measurement. To add a reference cell to ReRa Tracer open the Reference cell dialog from the 'Options' menu.

REFERENCE CELL MANAGEMENT

Press the add button and insert the required values. The Short Circuit Current (Isc) will later on be used to determine the irradiance level of the simulator.

## SIMULATOR IRRADIANCE

To inform ReRa Tracer about the exact irradiance level a reference cell has to be used. When the irradiance level is not set a warning is shown in the left-bottom corner of the main window.



It is required to add the reference cell to Tracer (see Reference Cells). To set the irradiance level an illuminated curve has to be measured of a reference cell. When the curve is measured the user has to press the 'Irradiance' button:

Select the reference cell from the dialog window that appears and the values will be used to set the irradiance level. From now on this level will be stored in all illuminated curves measured. If the intensity of the lamp changes, the irradiance has to be set again.

### MONITORING CELL TEMPERATURE

If a temperature monitoring device is connected (like the NOVUS myPCLab), it will be used to measure the temperature directly after an illuminated or dark curve. If there is a problem in controlling the device, a message will appear and the temperature will be automatically set to exactly 25°C



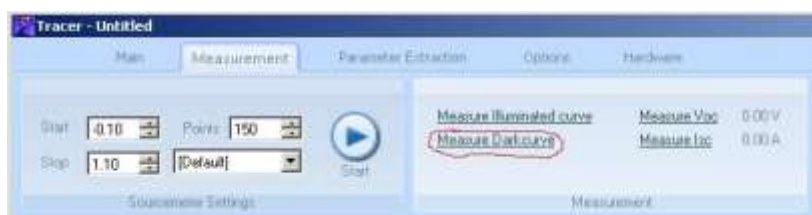
PRESS FIND TEMPERATURE TO INITIALIZE THE TEMPERATURE MEASUREMENT

If there is a problem with the NOVUS myPCLab, press the 'Find Temperature Unit' link on the Hardware menu. Here it is also possible to test the measurement of the temperature.

### MEASURING DARK CURVES

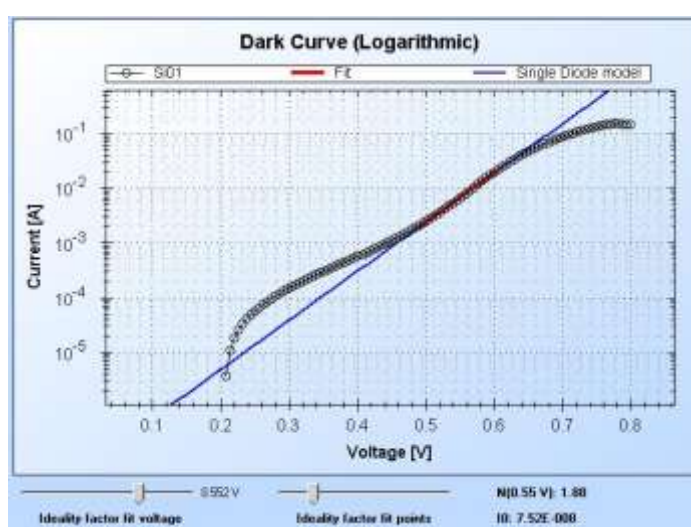
By measuring a dark curve of a solar cell, interesting parameters can be found. It will give information about the ideality factor and the dark currents. To measure a darkcurve the solar cell has to be in complete darkness. Even the lowest level of light entering the solar cell, will generate errors in the measured dark curve. Select '*Measure Darkcurve*' from the *Measurement* menu.





PRESS MEASURE DARKCURVE TO DISABLE THE SIMULATOR SHUTTER

After the measurement, the measured graph is shown on a logarithmic scale. This is the best way to look at a dark curve. In the curve a fit line is drawn that can be controlled by the two sliders below the graph. The line represents the values for the ideality factor ( $n$ ) and the dark current  $I_0$  at a certain voltage. The fit is a single diode fit, without any resistances. For higher quality fits, the user should install the required extension.

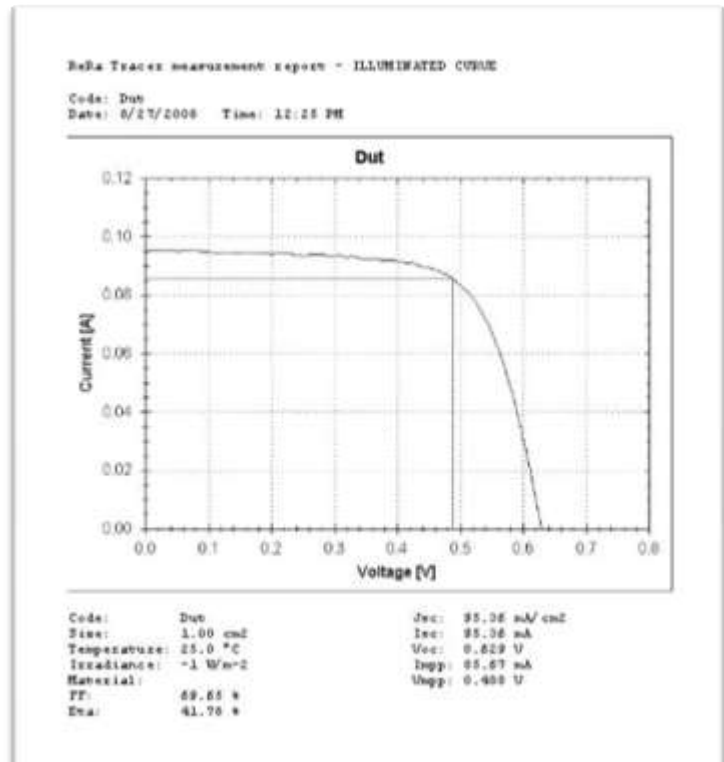


MEASURED DARK CURVE OF SILICON SOLAR CELL

This is a measured darkcurve of a silicon solar cell. The fit line shows an ideality factor of 1.88 at 0.55V. The measured dark current is  $7.52E-8$ . It is clear that the single diode model does not at all describe the solar cell in a good way. More analysis is necessary to obtain all solar cell parameters.

## REPORT GENERATION

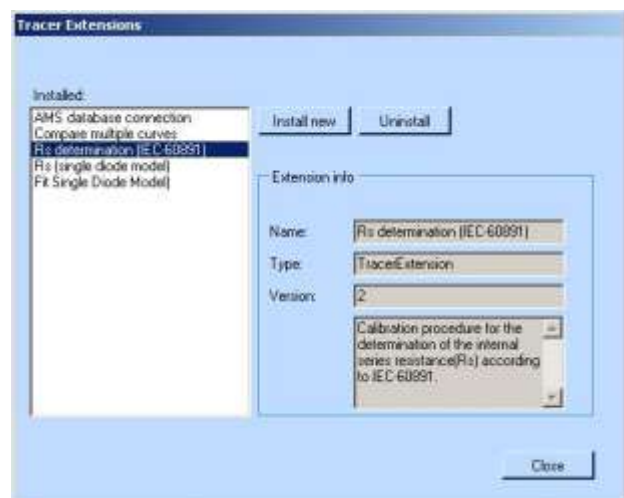
If a solar cell is selected the Print and Print Preview buttons on the Main menu can be used to create a measurement report.



EXAMPLE REPORT

## TRACER EXTENSIONS

The core ReRa Tracer application is an easy to use basic IV curve tracing application. In order to put more scientific value to the software solution, Tracer can be extended with free extensions. These extensions are downloadable from the ReRa website on request. New techniques in solar cell measurement technology will be added continuously. Feel free to suggest extensions. Adding and updating extensions is very simple. Just download an extension or update and store the file on a temporary location on your computer. Go to 'Options/Tracer Extensions' and install or upgrade the extension.



EXTENSION MANAGEMENT

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