FLUXiM
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paios

The revolutionary platform for all-in-one characterization of solar cells and OLEDs

- Charge Extraction
- Photo-CELIV
- Capacitance-Voltage
- IMPS / IMVS
- Impedance Spectroscopy
- MELS
- Current-Voltage-Luminance
- Emission Spectrum
- Transient Electroluminescence
- Transient Photocurrent
- Transient Photovoltage
- User-Defined Signals

All-in-One : Performs various experiments

Automated : Launch all measurements with one click

Reliable : Precise signals with high reproducibility

Overview

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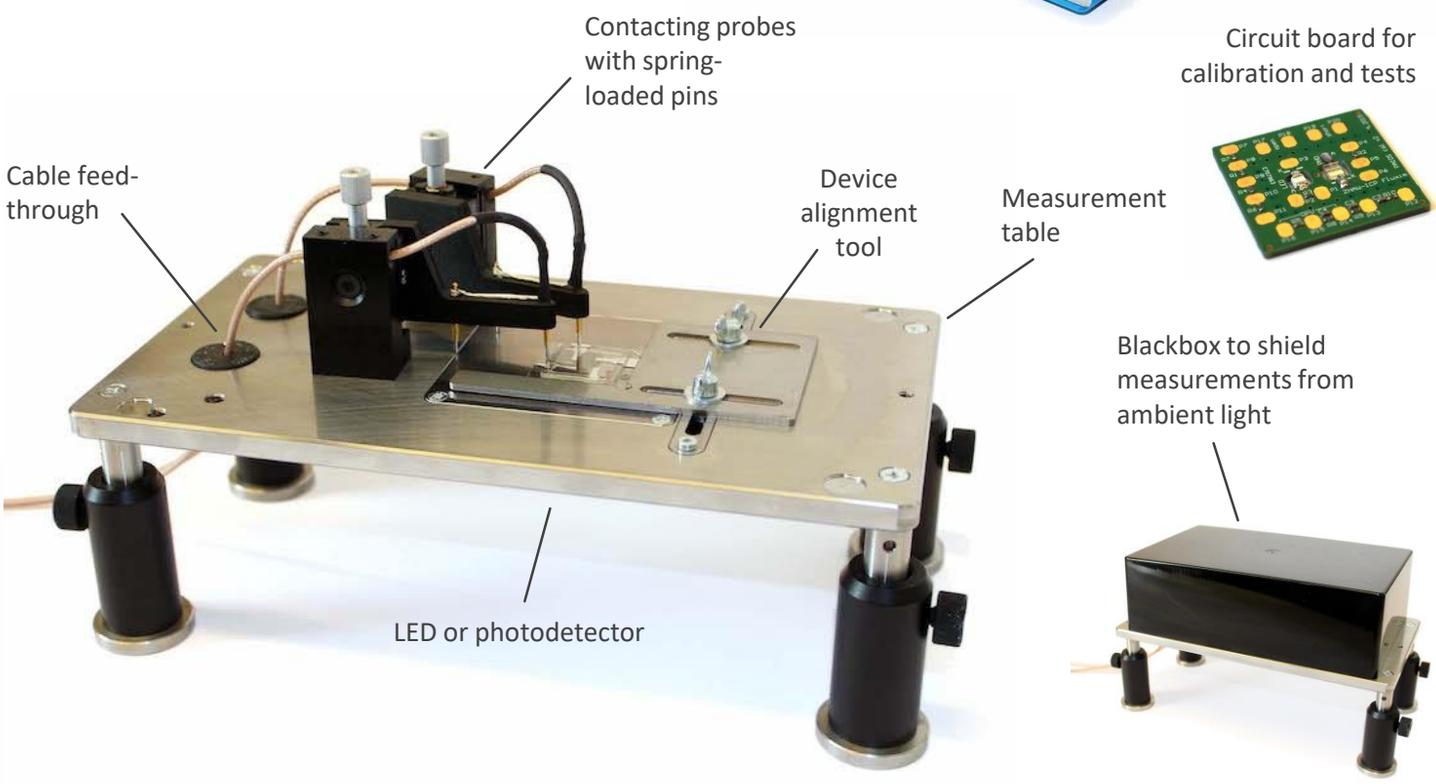
Delivery Content

The standard Paios comes with the following items:

- Desktop PC with preinstalled software
- Paios measurement system
- Measurement table with device alignment tool
- Blackbox for measurement table
- 2 contacting probes with magnetic feet
- Circuit board for calibration and tests
- High power LED (Paios for solar cells)
- Amplified photodetector (Paios for OLEDs)



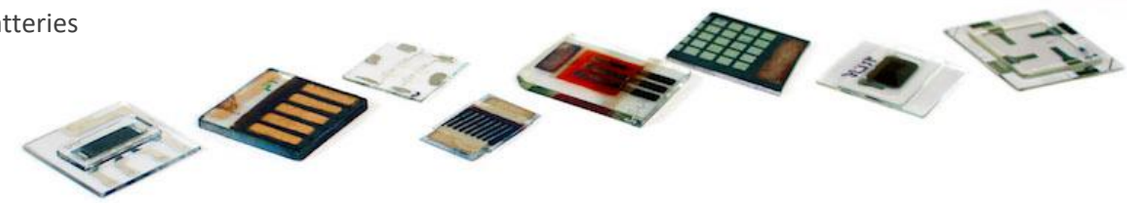
Specifications

Sampling rate	: 60 MS/s
Time resolution	: 16 ns
Voltage range	: ±12 V
Voltage range *(SMU module)*	: ±60 V
Frequency range of impedance	: 10 mHz to 10 MHz
Minimal resolvable current	: <100 pA
Maximum current	: ±100 mA
Measurement resolution	: 12 Bit
Typical meas. acquisition time	: 100 ms
Computer connection	: PXI / USB
Weight	: 15 kg
Dimensions	: 40 x 30 x 20 cm^3
Operating frequency	: 50/60 Hz
Operating voltage	: 100/240 VAC
Power consumption	: 75 W
Operating temperature	: 10° - 40° C
Operating relative humidity	: 10% - 90% noncondensing

Device Types

Device types that can be measured with **Paios**:

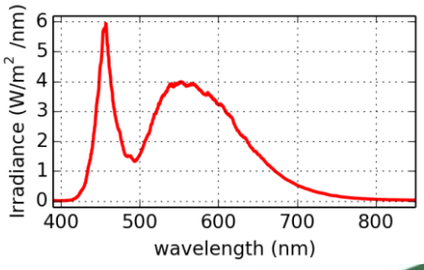
- Perovskite solar cells
- Organic, quantum dot and hybrid solar cells
- CIGS, CdTe, CZTS solar cells
- Dye-sensitized solar cells
- Solid-state thin-film Batteries
- Organic light-emitting diodes (OLEDs)
- Light-emitting electrochemical devices (LECs)
- Monopolar devices
- Metal-Insulator-Semiconductor (MIS) devices



Light Source

LED rise time	: 100 ns
Illumination area	: 1.7 cm^2
LED current	: 100 mA
Total optical power	: 60 mW
Color	: white

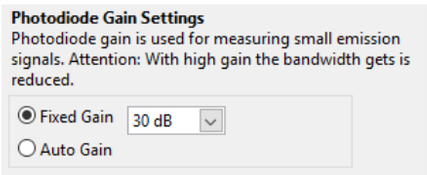
- High power LED to illuminate solar cells
- Other LED types are available upon request
- Check out the automated measurement table module for sun-simulator integration *(Page 15)*



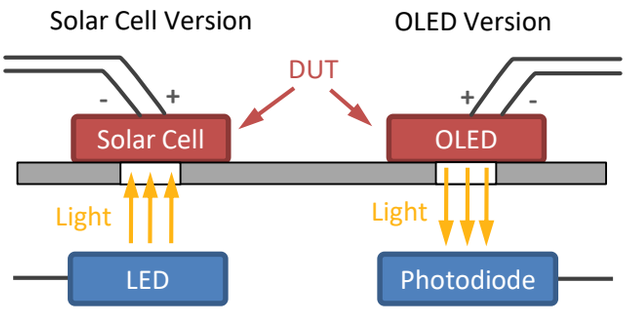
Photodetector

Amplifications	: 0 dB – 70 dB
Detector area	: 13 mm^2
Spectral sensitivity	: 350 – 1000 nm
Bandwidth at 0 dB	: 10 MHz
Bandwidth at 70 dB	: 5 kHz

- Amplified silicon photodetector to detect light emission
- Automatic gain switching controlled by software to achieve a high dynamic range in the EL signal

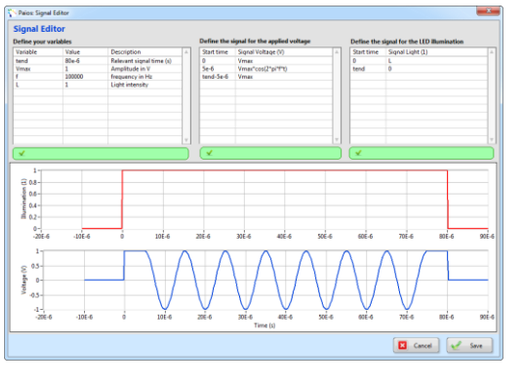


Paios for Solar Cells and OLEDs



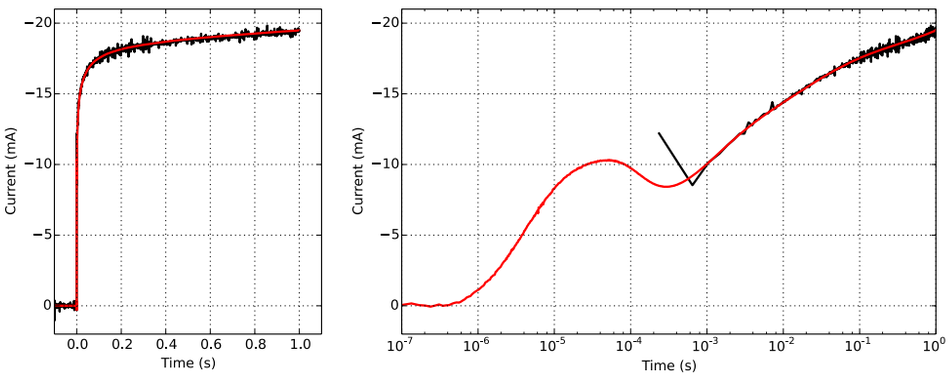
Paios is available in a version for solar cells and a version for OLEDs, either with an LED or with a photodetector. Both versions can also be combined in one **Paios**.

User-Defined Signals



Create your own experiments within minutes. With **algebraic expressions** any signal shape for transient illumination and applied voltage can be created easily.

Flexible Time-Resolution



Transient photocurrent of a perovskite solar cell with linear time scale (left) and logarithmic time scale (right).

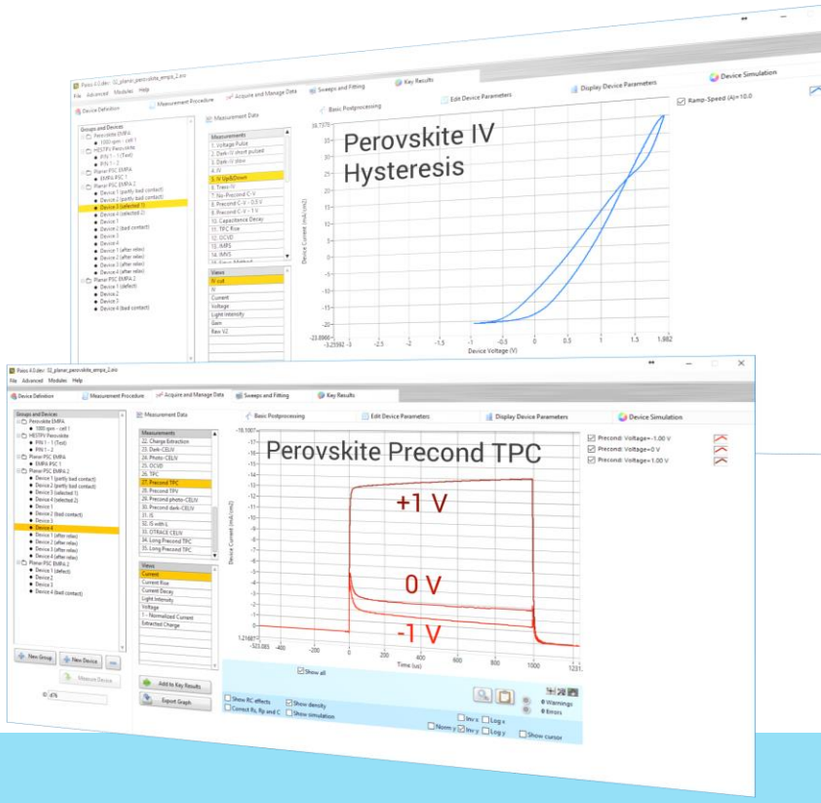
Traditional measurement setups use linear time sampling and can therefore only resolve about 3 orders of magnitude in time. Paios measures up to **8 orders of magnitude in time** in one shot.

Application: Perovskite solar cells can exhibit an extraordinarily broad dynamic range **from microseconds to minutes**.

Preconditioned Measurements for Perovskite Solar Cells

The response of perovskite solar cells depends on the “internal state” of the device prior to the measurement. It can lead to **hysteresis** in the IV-curve.

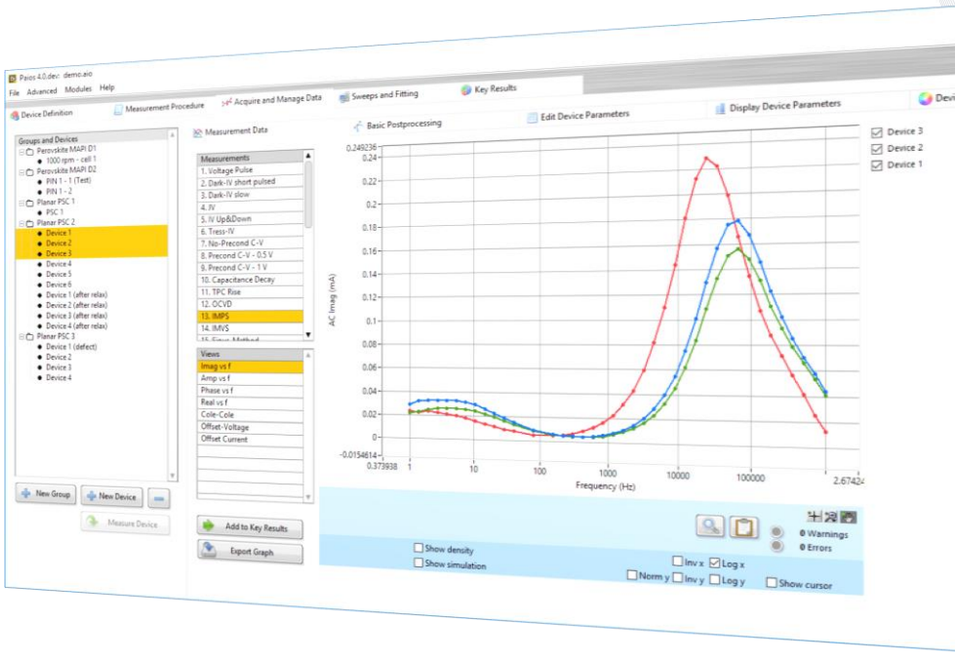
Paios can **precondition (prebias)** the device with voltage, current or illumination and perform the experiments shortly afterwards. With preconditioning the **reproducibility is increased drastically**.
Use this feature to investigate the effect of mobile ions, ferroelectricity or deep trap sites.



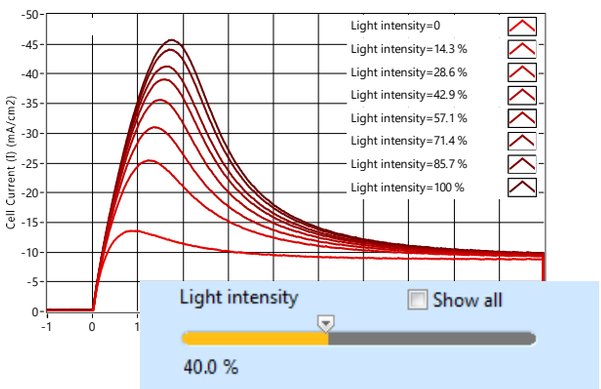
Data Management and Comparison

Paios is more than a measurement tool. Paios acquires systematic data of dozens of devices and lets you compare them in the Paios software.

- Internal database stores all measurement data
- Multi-select devices of interest and compare all measurement results
- Structure and organize your data
- Name and store key-results



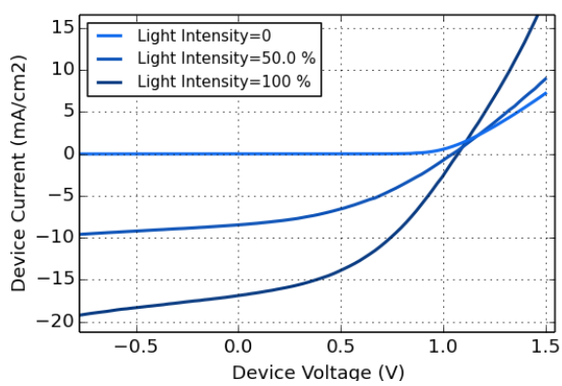
Parameter Sweeps



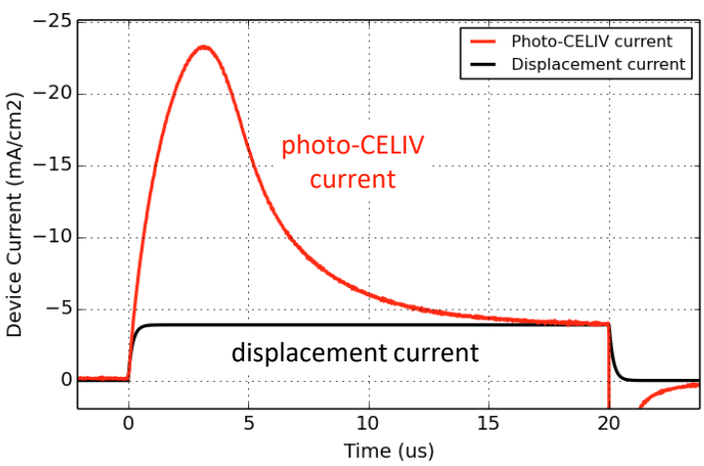
- Sweep measurement parameters
- Sweep types: linear, logarithmic, user-defined list
- Graphically inspect your dataset

Export Data

- Create publication-quality plots
- Export single plots as pdf, png, csv or python files.
- Automatically create measurement reports and export to PDF.



Plot generated by the Paios plotting engine.

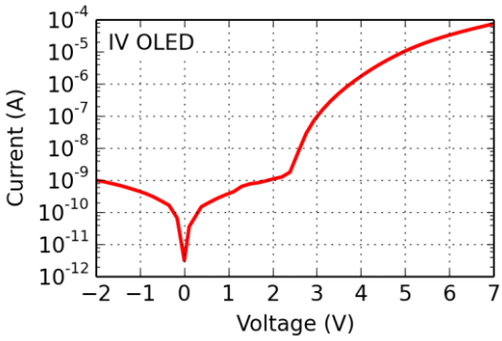


Correct RC-effects

RC-effects are superimposed on the device current and can significantly disturb transient experiments.

Paios provides routines to extract the series resistance and the geometric capacitance of the device. With these values the **displacement current** is calculated and the current can be corrected for the RC-effects.

IV(L) – Current-Voltage(-Luminance) Characteristics



For solar cells Paios automatically calculates the light **ideality factor** from the slope of the open-circuit voltage versus the light intensity.

The current-voltage characteristic is the most common measurement technique for electrical devices. For OLEDs also the luminance is measured.
There are 3 different methods in Paios to measure the IV-curve:

Ramped Measurement
The IV-curve is measured with one continues voltage-ramp. This is the fastest method to acquire an IV-curve.

Pulsed Measurement
The IV-curve is measured by single voltage-pulses. Herewith the highest current resolution is reached.

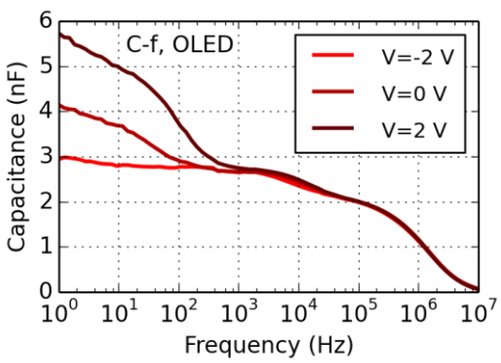
Sequential Measurement
This method measures the IV-curve point-by-point like a traditional SMU.

- Voltage range -10 V to +10 V
- Current resolution < 100 pA
- For solar cells and OLEDs

Available Postprocessing Routines

- Extracting the emission onset voltage of an OLED
- Extracting the mobility of a monopolar device from Mott-Gurney analysis (SCLC)
- Extracting the parameters of the one-diode model
- Extracting FF, Isc, Voc and MPP of a solar cell

IS - Impedance Spectroscopy



In impedance spectroscopy a small sinusoidal voltage is applied to the device and the complex impedance is measured according to amplitude and phase-shift of the current.

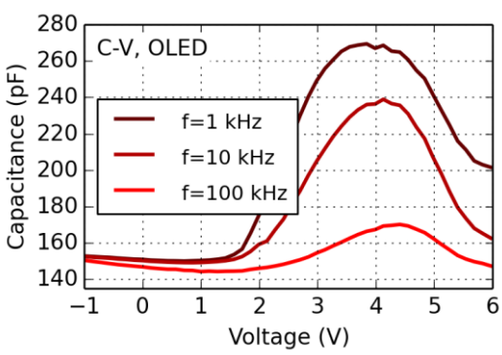
The technique is widely used to study solar cells and OLEDs. Charge carrier dynamics at different frequencies can be studied.

- Frequency range: 10 mHz to 10 MHz
- Impedances up to GΩ
- Offset voltage -10 V to +10 V
- For solar cells and OLEDs

Available Postprocessing Routines

- Fitting with Equivalent-Circuits
- Extracting series resistance, parallel resistance and the geometric capacitance

CV - Capacitance-Voltage



The impedance of a device is measured for varied offset voltage at constant frequency.

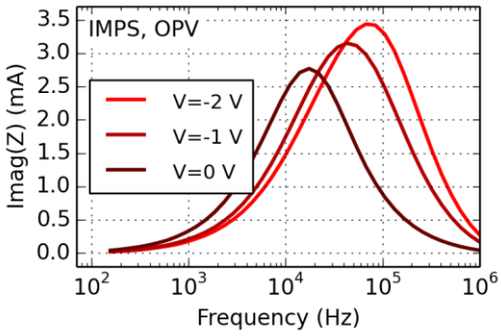
Capacitance-voltage curves reveal information about the built-in field and the charge injection barriers.

- Offset voltage -10 V to +10 V
- For solar cells and OLEDs

Available Postprocessing Routines

- Extracting the doping density by Mott-Schottky analysis

IMPS – Intensity-Modulated Photocurrent Spectroscopy



A solar cell is illuminated at short-circuit with a constant light intensity. On top of the constant light intensity a small modulated light signal is added.
The amplitude and the phase-shift is measured between short-circuit current and input light.

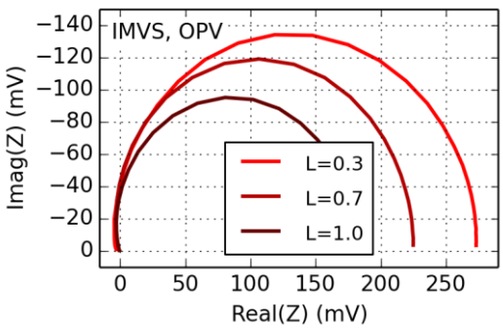
This technique is applied to investigate charge transport in solar cells.

- Frequency range: 10 mHz to 1 MHz
- Offset voltage -10 V to +10 V
- For solar cells

Available Postprocessing Routines

- Extracting the charge transport time from the IMPS peak

IMVS – Intensity-Modulated Photovoltage Spectroscopy



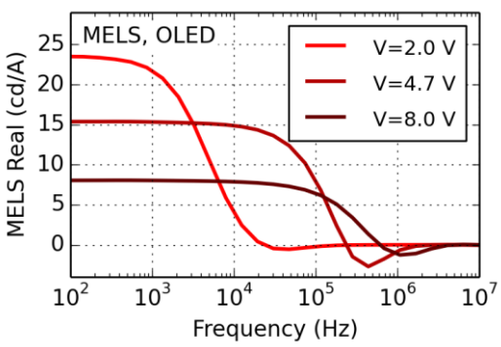
IMVS works like IMPS (above) but instead of keeping the solar cell at short-circuit, the solar cell is kept at open-circuit.
This technique is applied to extract the charge carrier lifetime in solar cells.

- Frequency range: 10 mHz to 1 MHz
- For solar cells

Available Postprocessing Routines

- Extracting the recombination time from the IMVS peak

MELS – Modulated Electroluminescence Spectroscopy

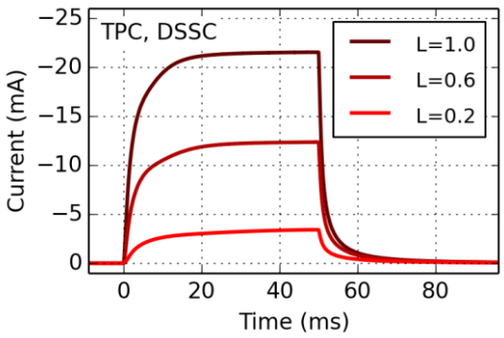


As in impedance spectroscopy a sinusoidal voltage is applied to the device on top of a constant offset voltage.
The amplitude and the phase-shift of the EL signal are measured versus various frequencies.

MELS is used to study the charge transport in OLEDs.

- Frequency range: 10 mHz to 10 MHz
- Offset voltage -10 V to +10 V
- For OLEDs

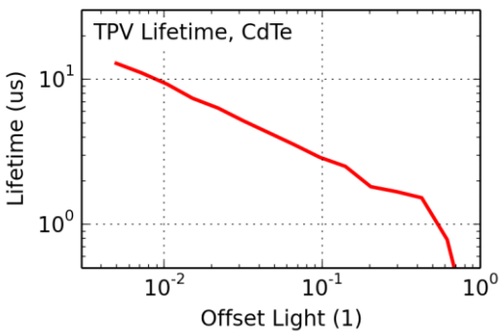
TPC – Transient Photocurrent



In this technique the transient current in response to the light turn-on is measured.
The shape of rise and decay provide information about **charge carrier mobilities**, their ratio and the dynamics of trapping.

- Pulse length: 1 µs to 1000 s
- Offset voltage -10 V to +10 V
- For solar cells

TPV – Transient Photovoltage



In this technique the solar cell is kept at open-circuit under illumination.
A short light pulse is applied that leads to a rise in voltage. After light pulse turn-off the voltage decays back to its previous value. From this decay-time the charge carrier lifetime is calculated.
Open-Circuit Voltage Decay (OCVD) can also be performed with this measurement technique.

- Automatic calculation of the charge carrier lifetime
- For solar cells

CELIV – Charge Carrier Extraction by Linearly Increasing Voltage

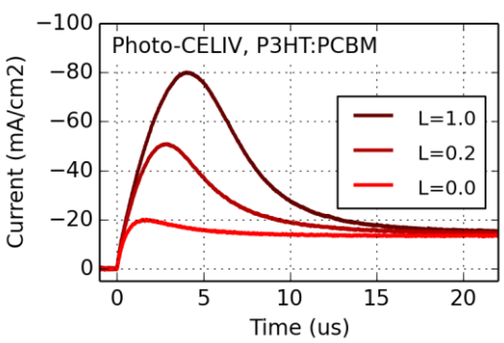


Photo-CELIV is a powerful technique to extract charge carrier mobility, the recombination coefficient and the doping density.

CELIV got popular for organic solar cells but can also be applied to perovskite solar cells or OLEDs.

A voltage ramp is applied in reverse to extract charge carriers. The current-peak is related to the charge carrier mobility.

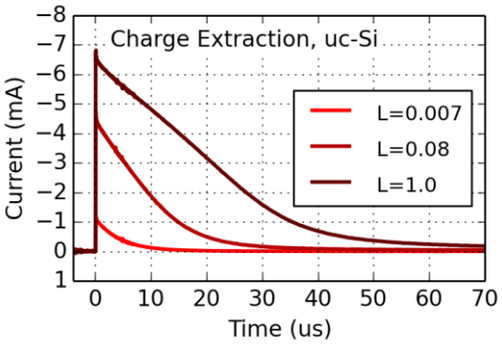
Paios uses the technique **OTRACE** to accurately determine the recombination coefficient of solar cells from photo-CELIV measurements with varied delay-time.

- For solar cells, MIS and OLEDs

Available Postprocessing Routines

- Extracting the charge carrier mobility
- Extracting the doping density from dark-CELIV measurements
- Extracting the geometrical capacitance and the series resistance from dark-CELIV
- Extracting the recombination coefficient of solar cells from OTRACE CELIV

CE – Charge Extraction



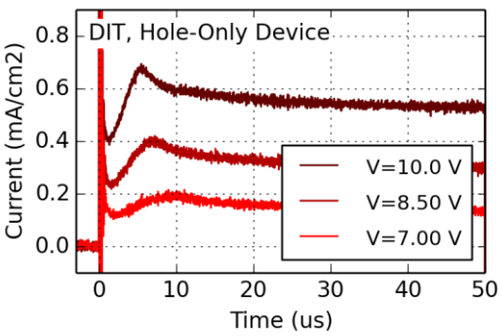
The solar cell is kept at open-circuit under illumination. Then simultaneously the light is turned off and the device is put to short-circuit to extract charge. Paios integrates the extraction-current to get the total **charge carrier density** that was in the device prior to the extraction.

- For solar cells

Available Postprocessing Routines

- Extracting the recombination coefficient from charge extraction with varied delay-time similar as in OTRACE.

DIT – Dark Injection Transients



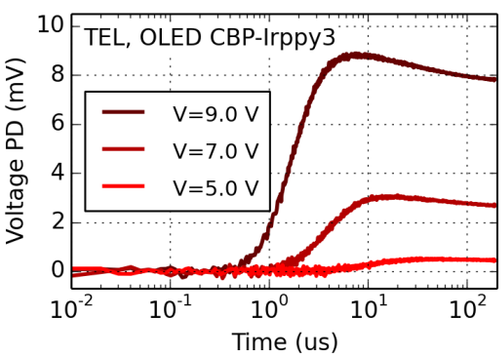
A voltage step is applied to the device and the transient current response is measured.
In monopolar devices with good contacts the charge carrier mobility can be determined from the current peak.

- For monopolar devices, solar cells and OLEDs

Available Postprocessing Routines

- Extracting the series resistance and geometric capacitance

TEL – Transient Electroluminescence



A voltage step is applied to an OLED and the transient EL signal is measured.
Analyzing the delay time between voltage turn-on and emission turn-on the average **mobility** can be calculated.
By studying the decay of the EL signal the **phosphorescence lifetimes** can be determined.

- For OLEDs and highly efficient solar cells

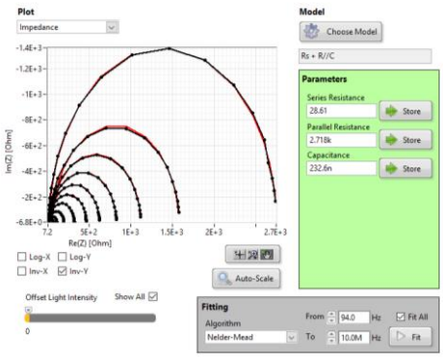
Available Postprocessing Routines

- Extracting the average charge carrier mobility
- Extracting the PL lifetime

Postprocessing for Parameter Extraction

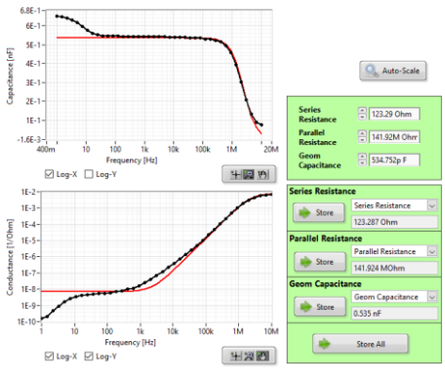
Paios comes with flexible and **user-friendly** post-processing routines included. Even novice users can easily analyze experimental results and **extract parameters**.

Equivalent Circuit Fitting



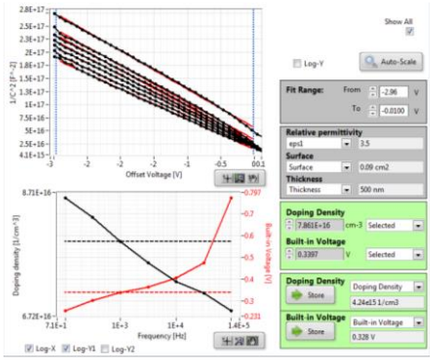
The most popular way to analyze impedance spectroscopy data is equivalent circuit fitting. Paios has integrated a routine for such fits. User-defined or pre-defined circuits are available.

Series Resistance and Geometric Capacitance from Impedance



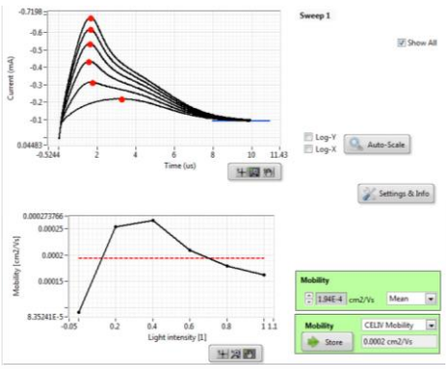
A very reliable method to extract the series resistance and the geometric capacitance from impedance spectroscopy data.

Mott-Schottky Doping Density from CV



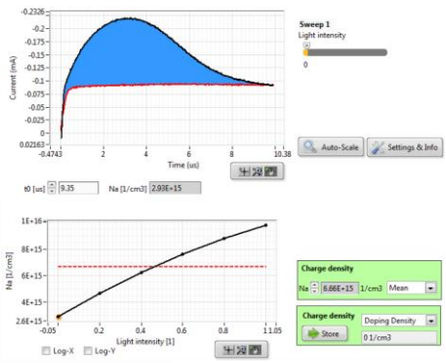
With a Mott-Schottky analysis the doping density of a semiconductor can be extracted from CV-measurements (provided the device is thick enough).

Charge Carrier Mobility from CELIV



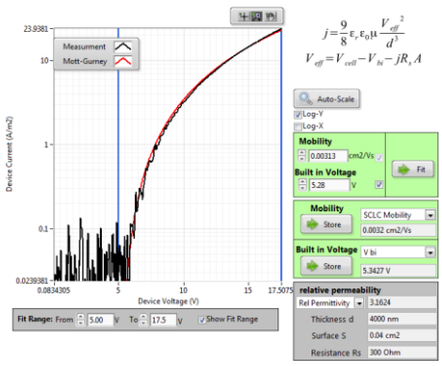
Extract the charge carrier mobility from CELIV experiments. The user can choose between several formulas to evaluate the mobility.

Doping Density from CELIV



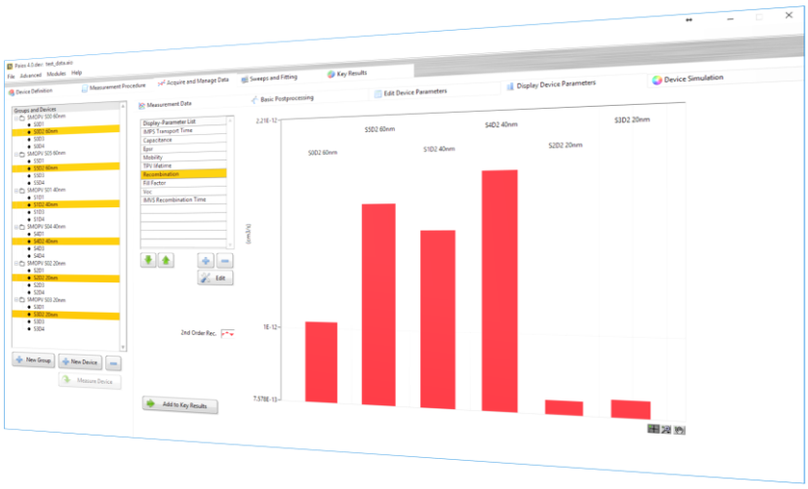
The dark-CELIV current overshoot (shown in blue) is integrated to obtain the doping density.

Charge Carrier Mobility from Mott-Gurney Fit

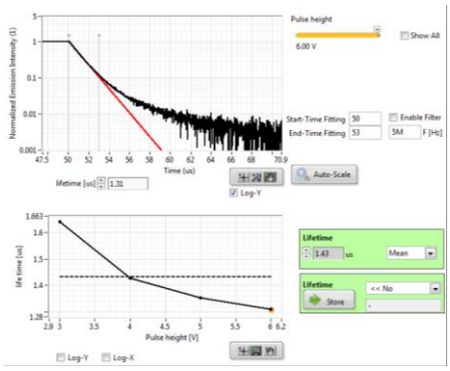


In monopolar devices the charge carrier mobility can be extracted from an IV-curve using a SCLC-fit.

Compare the parameters you have extracted in **Paios**, create and export bar-plots or xy-plots.

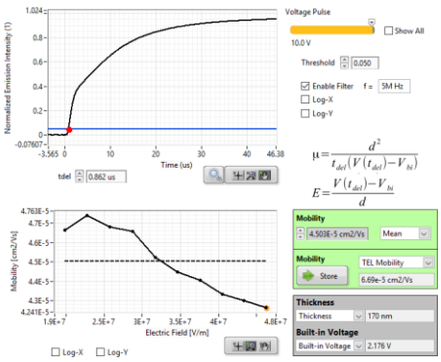


Luminescence Lifetime



From the electroluminescence decay after voltage turn-off the luminescence lifetime of the emitter can be extracted.

Mobility from Transient Electroluminescence

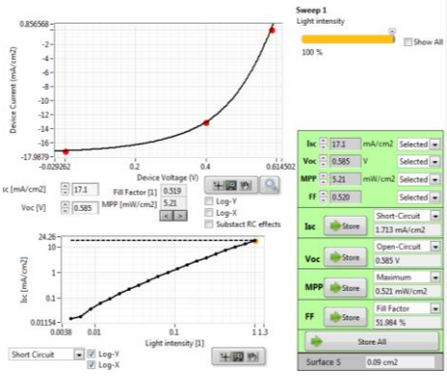


$$\mu = \frac{d^2}{t_{del}\left(V\left(t_{del}\right) - V_{bi}\right)}$$

$$E = \frac{V\left(t_{del}\right) - V_{bi}}{d}$$

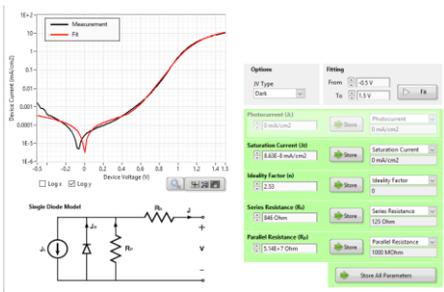
Extracts the charge carrier mobility from the delay time between voltage and EL turn-on.

Basic Solar Cell Parameters



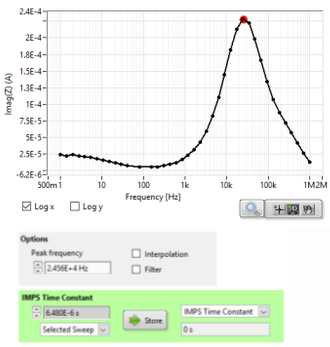
Extracts short-circuit current, the open-circuit voltage, the fill factor and the maximum power point of a solar cell.

One-Diode Model Fit



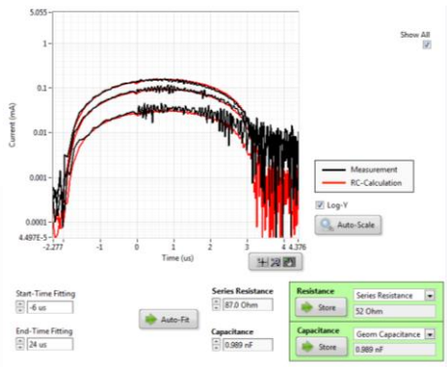
Extract the parameters of the one-diode model for solar cells: ideality factor, dark saturation current, series resistance and parallel resistance.

Transport-Time from IMPS Lifetime from IMVS



Easily determine the transport time from IMPS that describes how fast charges reach the contacts. From IMVS the charge carrier lifetime is determined.

Series Resistance and Permittivity from Voltage-Pulse

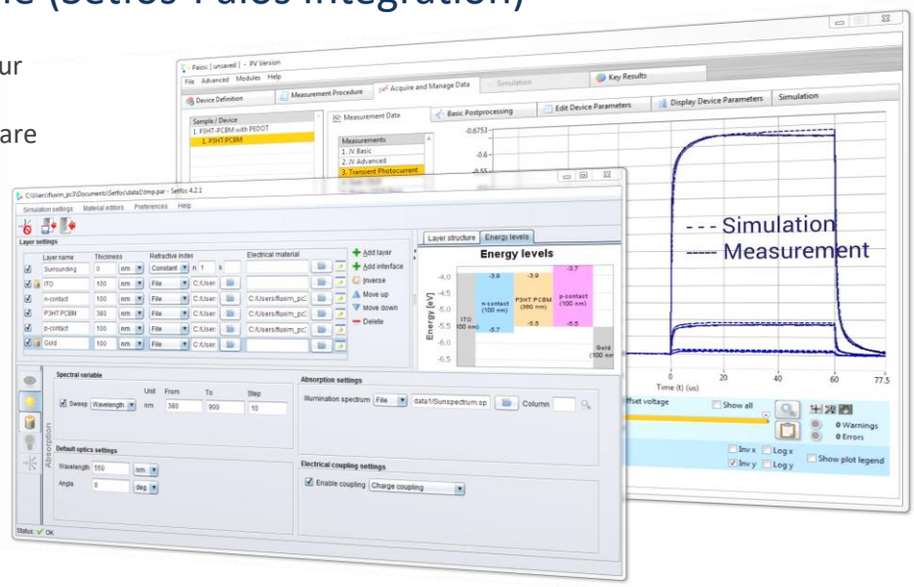


Determine the permittivity/ capacitance and the series resistance from a small voltage pulse in reverse.

Numerical Simulation Module (Setfos-Paios Integration)

Numerical simulation helps to understand your measurement results.
Therefore we integrated our simulation software Setfos seamlessly into the Paios software.

- Perform simulations of all Paios experiments
- Simulate **OLEDs** and **solar cells**
- Compare simulation and measurement directly in the Paios software
- Use our **global fitting** routine to extract device and material parameters
- Easy-to-use software interface



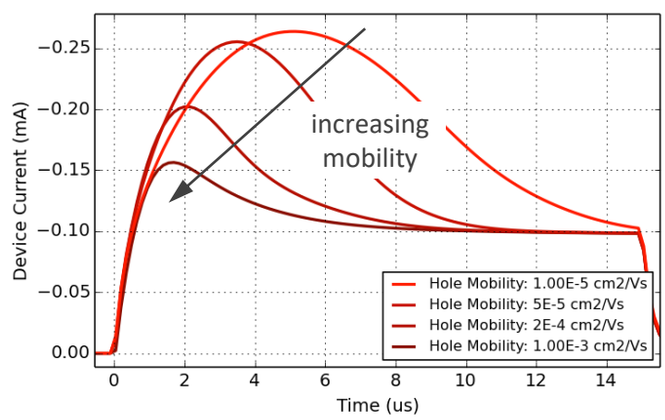
Parameter Extraction

Use the Setfos-Paios Integration to **extract device** and **material parameters**:

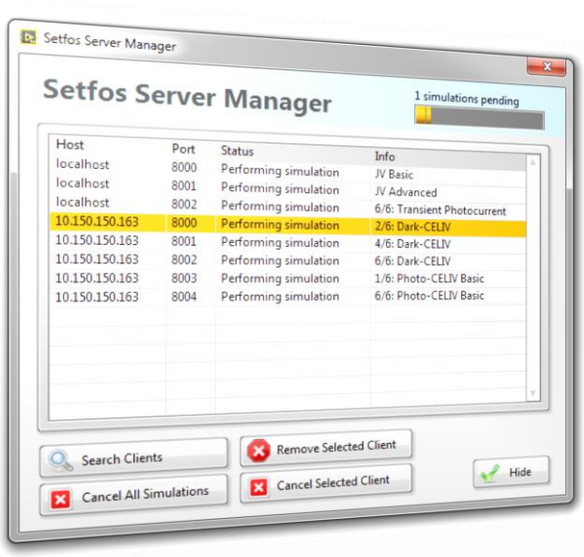
- electron and hole mobilities
- recombination coefficients
- charge injection barriers
- built-in voltage
- doping densities
- mobile ions
- trap parameters
- permanent dipole moments
- series resistance
- parallel resistance
- electrical permittivity
- ....

How Does a Material Parameter Influence an Experiment?

Use drift-diffusion simulation to analyze the influence of certain material parameters on an experiment. Easily **sweep** a simulation parameter to understand its influence.



Simulation of a photo-CELIV experiment with varied hole mobility.



Distributed Computing

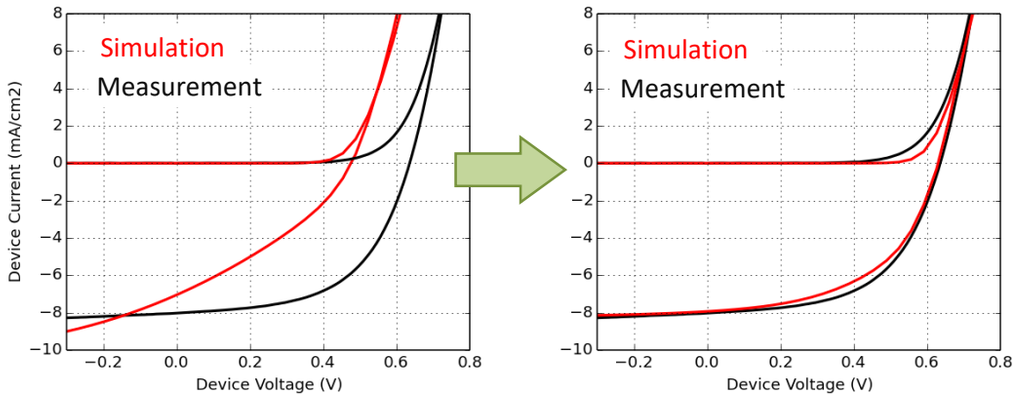
With the Setfos-Paios Integration calculations can be distributed on different computers over the network.

Save time by running simulations in parallel on different computers.

What is Fitting?

Fitting is a process where simulation parameters are adapted such to bring measurement and simulation result in agreement.

Fitting is used to extract parameters from experimental results.



IV-curve simulation (illuminated and dark) with initial parameter-set.

IV-curve simulation (illuminated and dark) after fitting.

Global Fitting of Experimental Results

If more than one experiment type is fitted simultaneously, this is called global fitting. The Paios software optimizes parameters in order to fit several experiments.

The user defines the targets (what to fit) and the parameters to optimize. The software does the rest.

Use global fitting to extract device and material parameters reliably and with **increased accuracy**.

What is Parameter Correlation?

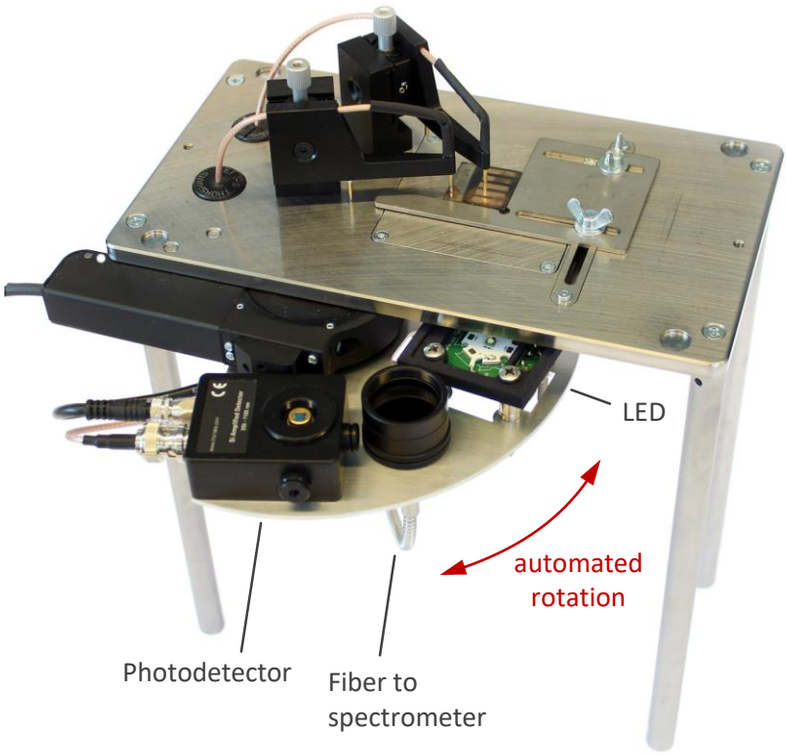
When two simulation parameters are correlated, it means they have a very similar influence on the simulation results. In this case the extracted parameters are not unique and therefore not reliable.

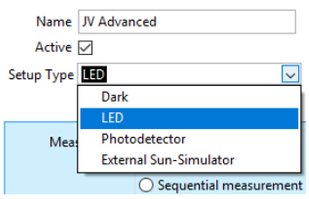
For each fit Paios automatically calculates a **correlation matrix**. The matrix shows the correlation between all parameters involved.

With the correlation matrix the user can judge how unique the fit is. By adding further experiments to the global fit the parameter correlation can be reduced.

	Electron-Mobility	Hole-Mobility	Opt Gen Eff	Epsr	Ref Eff	Built-In-Voltage	Anode Barrier	Cathode Barrier	N0	Polymer - Acceptor Doping (p-type)
Electron-Mobility	1.00	-	-	-	-	-	-	-	-	-
Hole-Mobility	-0.41	1.00	-	-	-	-	-	-	-	-
Opt Gen Eff	-0.01	0.30	1.00	-	-	-	-	-	-	-
Epsr	-0.25	0.21	0.04	1.00	-	-	-	-	-	-
Ref Eff	0.45	-0.92	-0.24	-0.04	1.00	-	-	-	-	-
Built-In-Voltage	-0.71	-0.08	0.10	0.17	0.10	1.00	-	-	-	-
Anode Barrier	-0.67	-0.13	0.05	-0.12	0.08	0.95	1.00	-	-	-
Cathode Barrier	-0.69	-0.20	0.06	0.17	0.22	0.97	0.92	1.00	-	-
N0	0.68	0.19	-0.05	-0.03	-0.18	-0.97	-0.97	-0.98	1.00	-
Polymer - Acceptor Doping (p-type)	-0.21	-0.03	-0.01	0.57	0.21	0.16	-0.03	0.31	-0.15	1.00

Automated Measurement Table





The automated measurement table **automatically switches** between measurement instruments and light-sources. It can be equipped with:

- LED light source
- Photodetector
- Spectrometer
- Empty space for existing sun-simulator
- Multi-LED and Nanosecond Pulser Module

For Solar Cell Research

All basic solar cell experiments are accessible with the white LED. In addition a **sun-simulator** place below the measurement table can be used in order to determine the power conversion efficiency. With the photodetector and spectrometer transient and steady-state electroluminescence of solar cells can be recorded. Everything automated. Everything with one click.

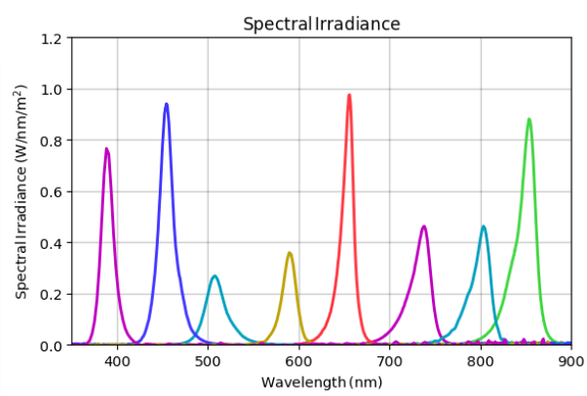
For OLED Research

Measure the OLED spectrum and transient electroluminescence without changing manually the measurement instrument or moving the device. Using a blue or UV LED Paios can also measure photo-responses of OLEDs.

Multi-LED Module

The automated measurement table is equipped with 15 additional monochromatic LEDs.

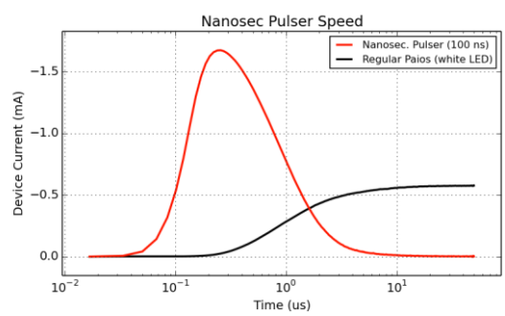
- Wavelength range 300-1100 nm (customizable)
- Absolute power and spectral calibration
- Measure mini-EQE



Nanosecond LED-Pulser

Experiments on solar cells and on OLEDs are often performed using a pulsed laser. This extension for the automated measurement table generates such short pulses.

- Pulse-lengths: 20 ns to 20 us
- With bias illumination
- Measure TPV, TPC, CELIV or CE using nanosecond LED-pulses



Paios (Low-)Temperature Modules

Varying the temperature of a semiconductor device is always interesting to investigate physics. Depending on the desired temperature range we offer different hardware solutions which are fully intregrated with Paios.

Liquid Nitrogen Cryostat

Temperature range :	**-150°C** to **+200°C**
Multiplexing :	1 pixel
Dewar size :	2 L
Filled dewar lasts for :	4 h
Maximum temperature ramp :	30 K/min

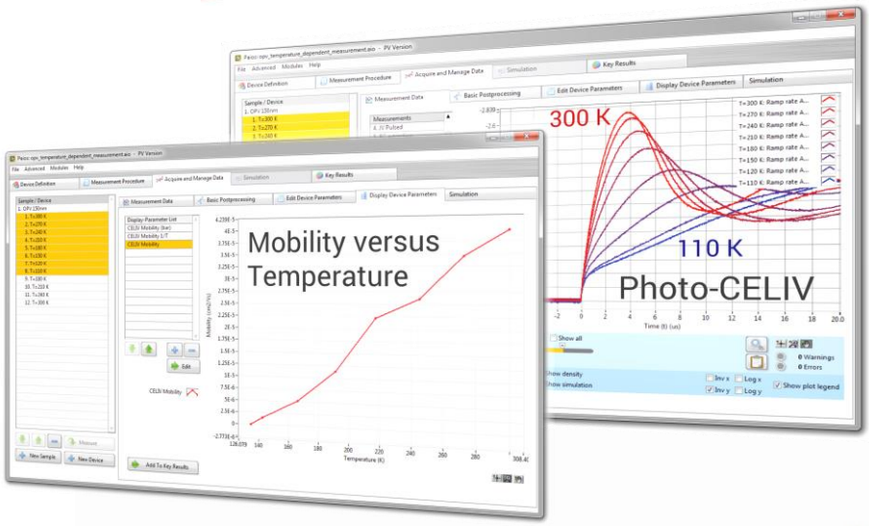
- Measurement chamber can be flushed with nitrogen to prevent condensation.
- Large available temperature range

Peltier Cooling Unit

Temperature range :	**-50°C (-20°C)** to **+80°C**
Multiplexing :	4 pixels
Maximum temperature ramp :	10 K/min

- Cooling by Peltier elements (no liquid nitrogen required)
- Available with liquid (-50°C) or air (-20°C) cooling
- Includes customized sampleholder and multiplexing
- Chamber can be evacuated or flushed with inert gas

- Perform all Paios experiments at low temperature
- Automatic temperature control and data acquisition
- Compatible with OLED and solar cell version and Automated Measurement Table
- Compatible with top-contact, bottom-emitting OLEDs and bottom-illuminated solar cells.
- Investigate thermal stability at elevated temperatures.



Stress-Test Module

- Monitor device degradation
- Stress by constant current, voltage and/or illumination
- Fully automated stressing, characterization and data acquisition
- Get highly consistent datasets
- Understand the origin of degradation of your device

SMU (Extended Voltage) Module

The SMU module is an extension to Paios that allows to apply and measure voltages up to 60 Volt.

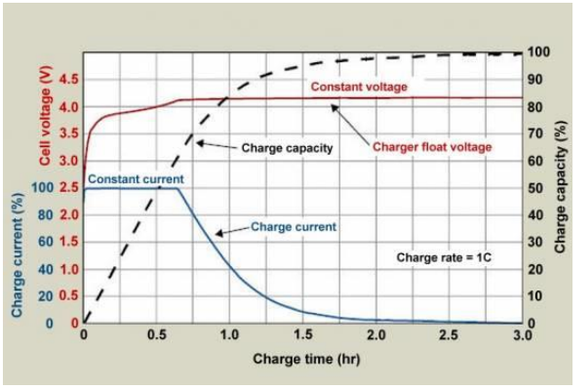
- Choose for each experiment whether to use the SMU mode or the regular Paios
- Increase your current resolution
- Measure impedance spectroscopy, IV-curves and transient experiments with high voltages.
- Can also be used for stressing and long-term measurements

Voltage range :	±60 V
Min measurable current :	1 pA
Frequency range impedance :	10 mHz to 1 kHz
Sampling Frequency :	100 kS/s

Battery Module

The Battery module uses the SMU and the Stress-Test module for characterization of solid-state thin-film batteries.

- Automated charge-discharge cycles
- Cyclo-voltammetry
- Impedance



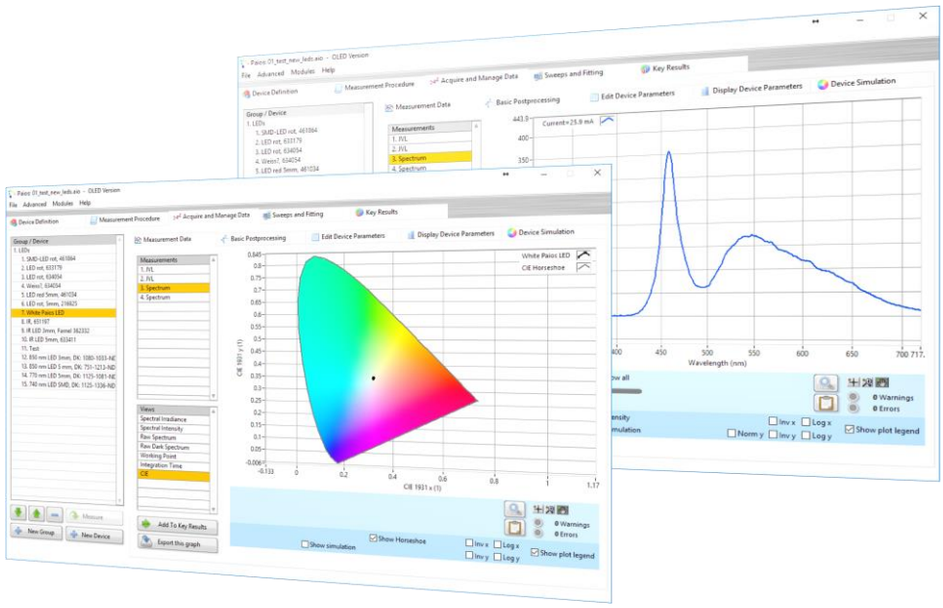
Multiplexing Module

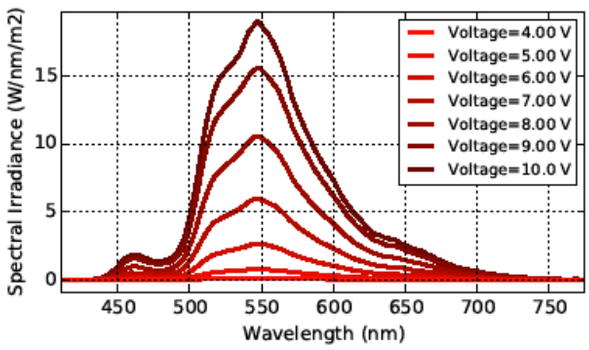
Quantitative conclusions from experiments usually require **statistics**. With the Paios multiplexing module devices are measured sequentially after each other.

- Connect up to 4 devices simultaneously
- Measure 4 devices automated after each other
- Most useful in combination with a **customized sample holder**

Spectrometer Modules

- Measure the emission spectrum of your OLED or solar cell
- Calibrated spectrometer
- Automatic dark-spectrum correction
- Most powerful in combination with the **automated measurement table**
- Different spectrometers available

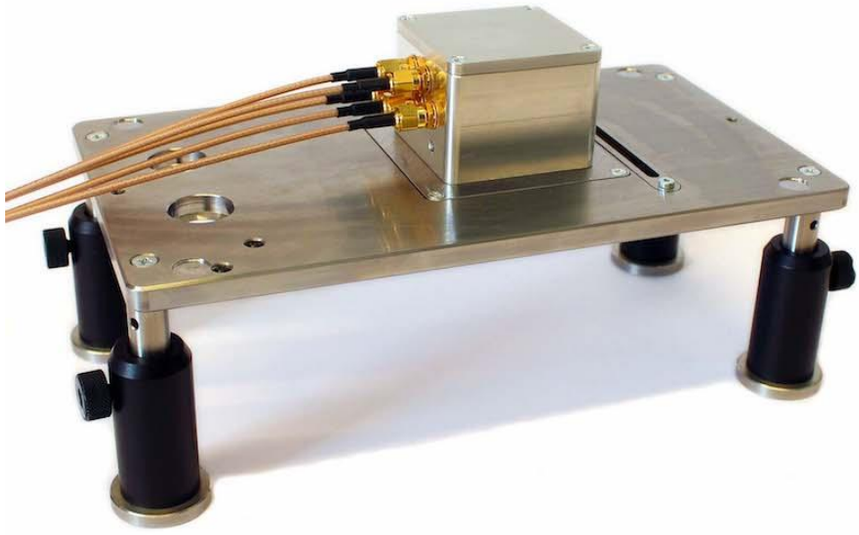




Spectral range :	360 – 880/1100 nm
Integration time :	1 ms to 10 min
Postprocessing quantities :	luminance, radiance, EQE, lm/W, CRI, CIE coordinates

Customized Sample Holder

- We offer customized sample holders for your device layout
- Connect up to 4 devices
- The device is contacted from the top by spring-loaded pins resulting in a **well-defined electrical contact**.
- Combination with the **automated measurement table** is possible.
- Includes 4-times Multiplexing

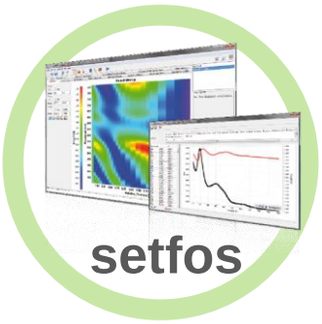


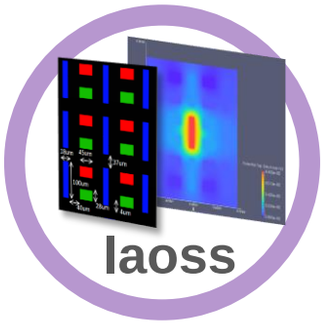
Glovebox Feedthrough

Paios can be used in combination with a glovebox. Upon request we provide **customized cable feed-throughs** for your glovebox.

Paios is placed outside the glovebox and the measurement table or sample holder can be used inside the glovebox.

Other Fluxim Products





PL & EL Angular Spectrometer

- Angular spectrometer to analyse emitter distribution and orientation
- Measure EL, PL, Lm/W, Cd/A as a function of the emission angle and determine EQE

OLED/PV Stability Analysis

- Stress-test platform for up to 32 devices in parallel
- Control temperature, light, atmosphere and working point (MPP tracking)

OLED/PV Design Software

- User-friendly thin film stack design software for OLEDs and solar cells
- Combined electronic, excitonic and optical simulation

Large Area 2D/3D Simulator

- Easy-to-use large-area software for OLED and solar cell modules
- Optimize electrodes with coupled electro-thermal modelling

Contact us

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