Graphical Abstract

4-wire I. and IV. quadrant IV characterization measurement setup for photovoltaic cells

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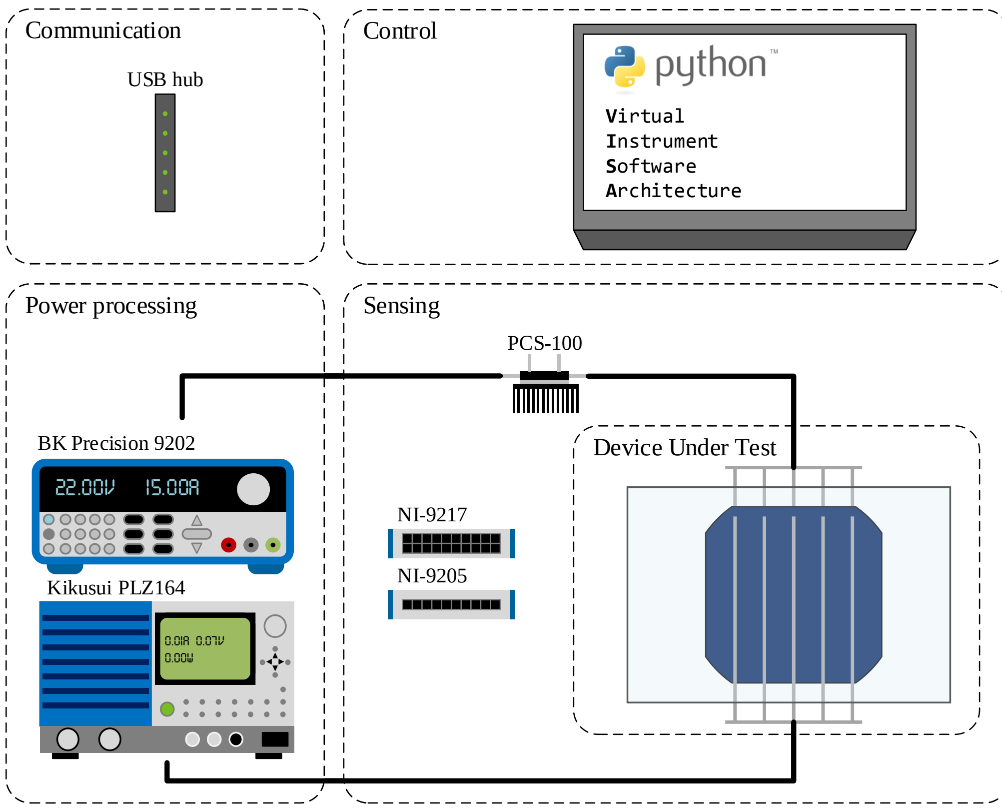

Highlights

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- Simple and high-power IV characterization in I. and IV. quadrant
- Python script controlling multiple devices connected to single computer
- Source code built on open-source libraries

4-wire I. and IV. quadrant IV characterization measurement setup for photovoltaic cells

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Abstract

Precise IV characterization of photovoltaic devices forms the basis of benchmarking novel photovoltaic designs. But when the device leaves experimental stage of small factor samples (e.g. 2 cm^2) and moves to mass production scale applied on 156×156 mm mono-Si wafers, the power processing part of the measurement system needs to scale linearly and process currents up to 120-times larger. The electric current ceiling grows even more when deep reverse-bias characteristic is being examined, where the dissipated energy can grow another 20-folds. This poses an issue even for laboratory-level multi-quadrant voltage sources.

This paper introduces simple and open-source solution for measuring I. and IV. quadrant of PV cell IV characteristic. The proposed measurement system is built around electric load and voltage source, with National Instrument (NI) cards for recording voltage, current and temperature throughout the measurement. Despite the NI-cards depending on proprietary software, we have managed to integrate the control within a Python script.

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1. Introduction

Obtaining precise, accurate and repeatable measurement is a fundamental basis of any research. Throughout our work on characterizing bifacial photovoltaic cells along the IV characteristic available to power processing device. Since the power connected device mainly extracts the energy of multiple cells in series, this limits the required controllable current I to positive value only. Therefore, the main concern of the required IV characterization is the I. and IV. quadrant as illustrate in Figure 1

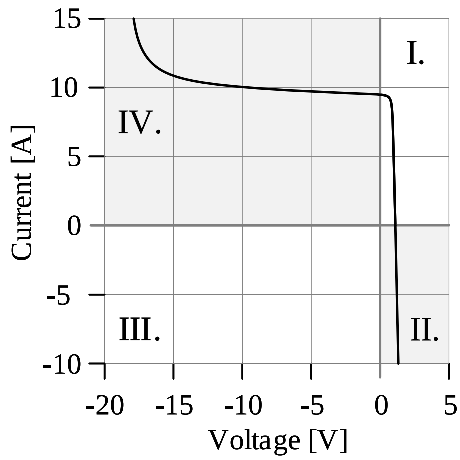

Figure 1: IV characteristic of a typical PV cell.

The IV characteristic spans 3 quadrants:

- I. quadrant hosts the generative part, which is crucial for determining peak performance, so called Maximum Power Point (MPP). This part is delimited by short-circuit current I_{SC} on y-axis and open-circuit voltage V_{OC} on x-axis.

- II. quadrant shows forward biased characteristic beyond V_{OC}. For common mono-Si PV cells this region is dominated by serial resistance R_s, thus linear.

- IV. quadrant shows the reverse-bias characteristic with typical "knee" for semiconductor devices, where the avalanche-breakdown cases exponential rise in current I. Before reaching the exponential rise of current I, this region is dominated by shunt resistance R_{sh}.

For the purpose of researching degradation in bifacial PV cells under illumination, our goal was to document changes causing the operating point to shift from MPP to reverse-bias. The main motivation for relating degradation level of different degradation modes, for instance Potential Induced Degradation (PID) or cracks, to the changes of operating point, is the formation and detection of hot-spots.

Despite the photovoltaics being a mature field, with well established standardized testing, the novelties in the field may overwhelm the capabilities of laboratory hardware easily. A good example are bifacial PV cells, where the testing under illumination can lead to almost 2-times larger currents compared to monofacial PV cells. Such experiments can easily surpass the maximum allowed current for many multi-quadrant sourcing and measurement units (SMUs). As an example, the typical IV characteristic is superimposed on a operating region of high-power SMU, Keithley 2651A, with highlighted region of interest in Figure 2.

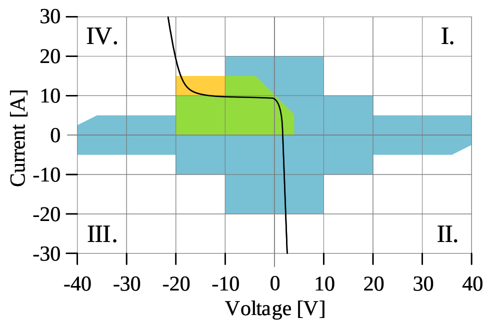

Figure 2: 4-quadrant SMU operating region with super-imposed IV characteristic of a bifacial PV cell. The region of interest is highlighted in yellow, the overlapping region is in green.

This shows that studying reverse-bias characteristic of a bifacial PV cell with top-of-the line laboratory hardware may pose challenges.

2. Hardware

The full list of requirements on the measurement device are as follows:

- sourcing up to 15 A to probe the avalanche-breakdown part of reverse-bias IV characteristic

- controlled speed of voltage-sweep at different parts of IV characteristic
- operating point control with feedback from sensors
- hardware-guaranteed/software-independent safety features
- unified programming environment interface
- expandable sensing hardware (e.g. multiple voltage or temperature probes)

These requirements exceeds the capabilities of many closed-source systems, since the programming of the devices often relies on proprietary software, making integration of high-end and high-level devices difficult.

2.1. Operating principle

The following outlines the operating principle of the proposed measurement setup. The measurement setup is

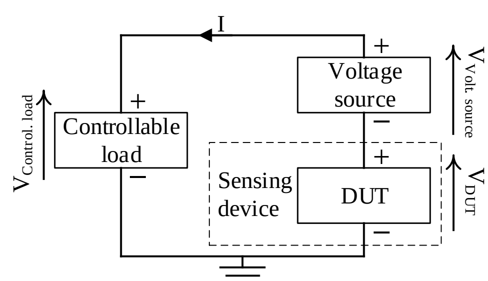

Figure 3: Diagram of electrical connection of devices comprising the measurement setup connected to a Device Under Test (DUT)

Brief explanation of operation constraints as well as safety features within the operating region:

- Controllable load controls the total voltage across the Voltage source and DUT.
- Voltage source provides voltage offset, such that $V_{Control.load} = V_{Volt.source} + V_{DUT}$. Since $V_{DUT} < 0$ at high current I as can be observed in Figure 1. The voltage source provides hard limit of reverse-bias voltage, such that minimum V_{DUT} is $V_{DUT} = -V_{Volt.source} = V_{MIN}$ when $V_{Control.load} = 0\ V$.

- Voltage source also provides hard limit of maximum sourced current I_{MAX}, thus safely limiting the maximum current passing through DUT.
- Maximum processed power at the Controllable load is $(V_{Volt.source} + V_{DUT,MPP}) \times I_{DUT,MPP}$.
- Sensing device senses voltage and current independently, relative to its respective ground. Therefore, differential voltage measurement is required.

The operating region of the measurement setup and the comparison to the sensed voltage and current are illustrated in Figure 4.

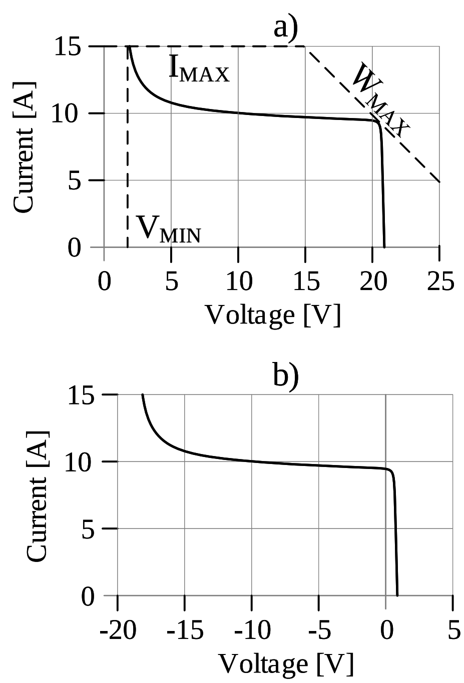

Figure 4: IV characteristic as it appears from the point of **a)** Controllable load, **b)** Sensing part. The diagram **a)** highlights the boundaries of the operating region as illustrated by highlighted area in Figure 2.

2.2. Proposed measurement setup

Following the operating principle outlined in section 2.1, the proposed measurement setup can be assembled from the following components:

- Computer to run the control and provide user interface
  - At least 1×USB 2.0.
  - Running Windows operating system.
  - Python 3.6 or higher installed.
  - VISA from National Instruments version 20.0 or higher.
- Voltage source capable of sourcing 15 A with USB interface.
  - BK Precision 9202 with USB interface enabling SCPI command transfer.
- Controllable load providing voltage control and capability to sink 15 A with USB interface.
  - Kikusui PLZ 164 WA with USB interface enabling SCPI command transfer.
- Voltage and current measurement devices communicating over USB.
  - National Instrument measurement card NI-9205 with NI-DAQx chassis with USB interface.
  - PCS-100 1.0 Ω sensing resistor.
- USB hub.
  - Self-powered USB hub with 4 (optionally 5) USB connections.
- (optional) Sensing device for temperature measurement using thermocouple.
  - National Instrument measurement card NI-9217 with NI-DAQx chassis with USB interface.
  - K-type thermocouple.
- High-power cables for power processing part.
- signal wires for 4-wire connection.
- USB cables.

The connection of devices is illustrated in Figure 5.

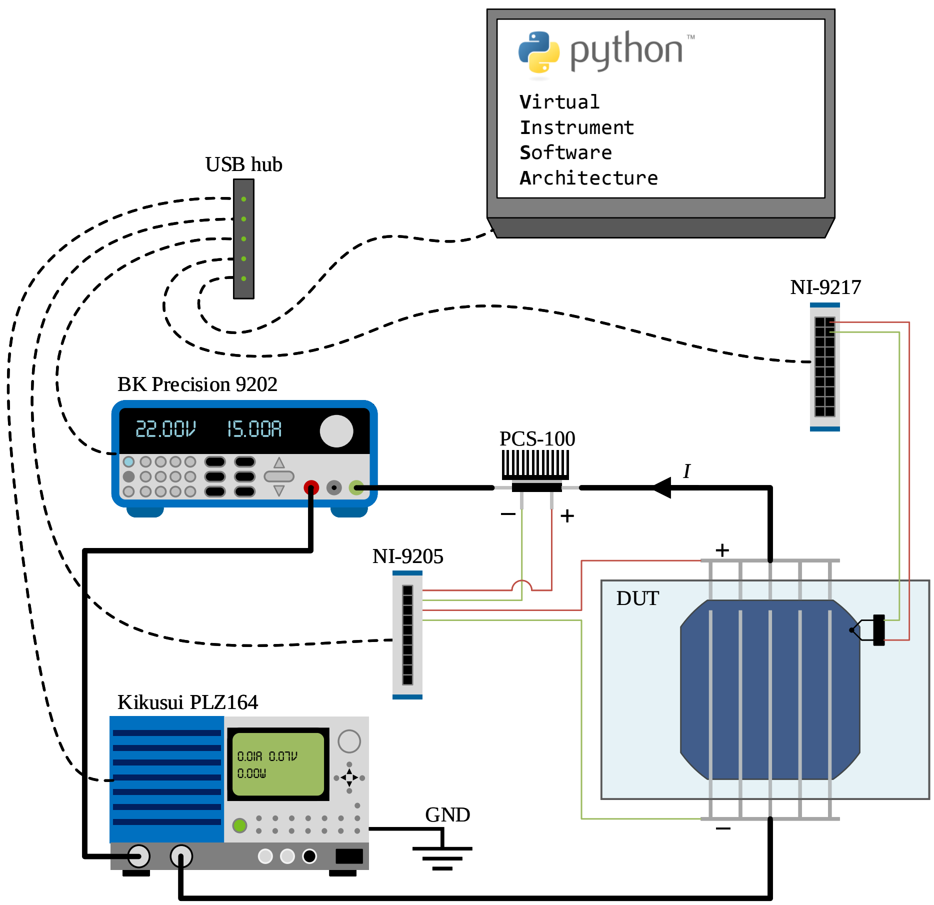

Figure 5: Illustration of connected devices in a 4-wire connection to Device Under Test.

3. Software

The software is an important part of the developed measurement setup, since it differentiates it from other measurement setups with closed-source code. We advocate for open-source solutions since proprietary software should not stand in the way of scientific progress. Therefore, the software providing complete control over the measurement setup is based on Python 3 using open source packages. The list of packages is listed below accompanied with the version and the type of open-source license.

package	version	license
pyvisa	1.11.3	MIT
nidaqmx	0.5.7	MIT
numpy	1.19.2	BSD
matplotlib	3.3.2	PSF
time	(built-in)	PSF
json	(built-in)	PSF
tkinter	(built-in)	PSF
os	(built-in)	PSF

Table 1: Packages used within the software, type of open-source licenses are included for clarity.

The *(built-in)* in Table 1 refers to built-in libraries for Python 3.6.

3.1. User Interface

User Interface provides intuitive way to control the software. The users input is kept in run-time variables, such that no change to code is required. Upon running the **TopScript.py**, the user is presented with the screen shown in Figure

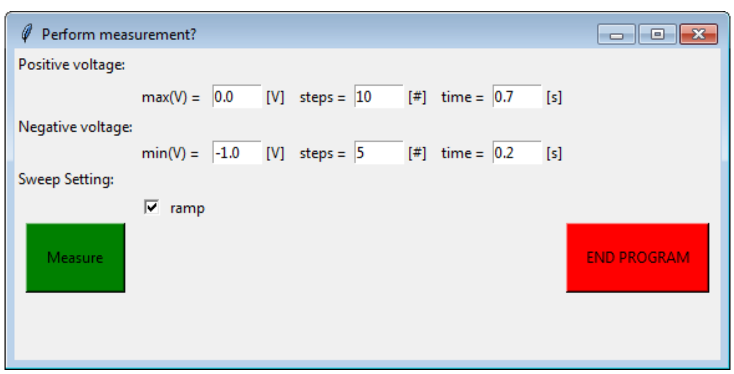

Figure 6: User interface prompting the input of parameters required to perform voltage sweep.

- **Positive voltage** - voltage sweep parameters in I. quadrant
  - max(V) - maximum voltage in volts, e.g. V_{OC} of PV cell
  - steps - number of steps inserted between 0 and $max(V)$

  - time - time duration of perturbation in seconds

- **Negative voltage** - voltage sweep parameters in IV. quadrant
  - min(V) - minimum voltage in volts, e.g. $V_{reverse-bias}$ of PV cell
  - steps - number of steps inserted between 0 and $min(V)$
  - time - time duration of perturbation in seconds

- **Sweep setting** - if ticked, then steps are linearly interpolated, if not ticked, then step-wise perturbation is performed

- **Measure** - button to start the measurement

- **END PROGRAM** - immediately stops the execution of the script and returns the control to Python interpreter

- **Change folder** - button to select the folder for saving data files

- **File name** - base-name of the files being saved, for instance *DUT_5* will generate files:
  - DUT_5_IV.csv - comma-separated values file containing the measured voltage and current vector
  - DUT_5_IV.png - screenshot of a figure with measured data containing the I-V plot and V-time, I-time plot of measured values
  - DUT_5_info.txt - text file containing user provided parameters in *User interface* from Figure 6 and the information provided below

- **Measurement details** - User defined information for simple identification of measurements in post-processing step, data are saved in JSON format

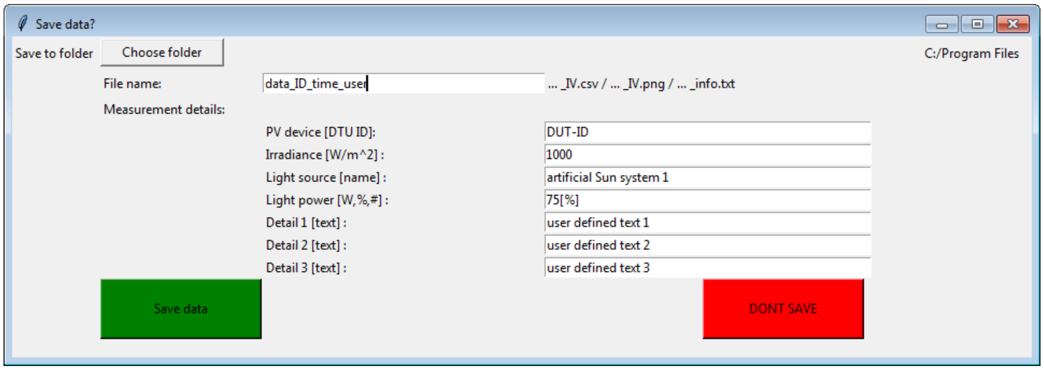

Figure 7: User interface prompting the input of parameters to save the data onto the local disk.

An example of a *data_IV.png* is shown in Figure 1.

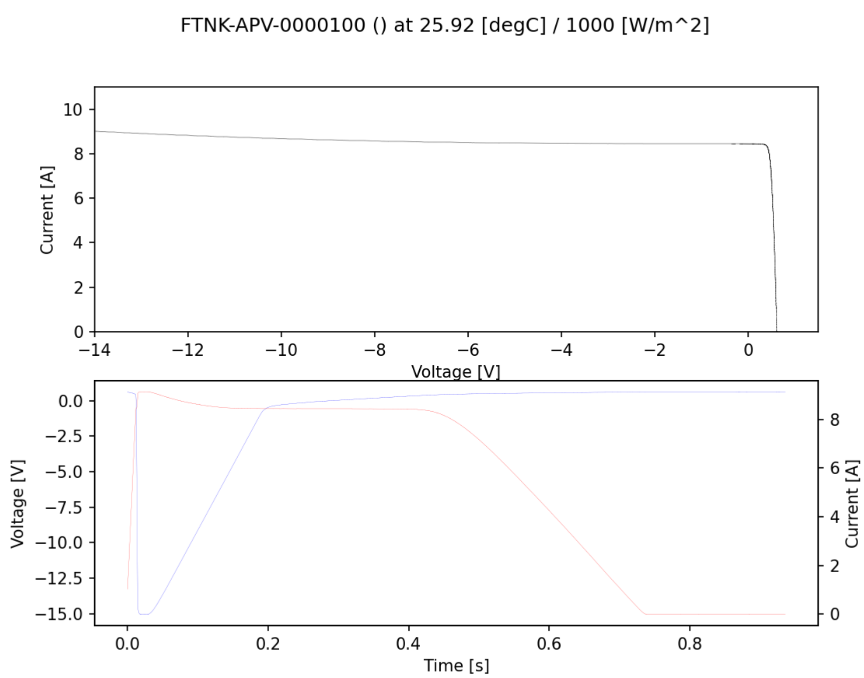

Figure 8: An example of data measured by the TopScript.py when tested on bifacial PV cell reverse-biased to $-14.0\ V$.

3.2. Software structure

The control software keeps a flat hierarchy with object-oriented approach to representing the connected devices. Every physical device and User Interface window is represented by a separate class. The folder tree in Figure 9 shows the whole structure of the control software.

Figure 9: Folder structure containing the control software in an easy-to-navigate flat structure.

```
/controlSoftware
 ├─TopScript.py (??)
 └─/lib
    ├─/BKPrecision9202
    │  ├─__init__.py
    │  └─device.py (??)
    ├─/KikusuiPLZ164WA
    │  ├─__init__.py
    │  ├─device.py (??)
    │  └─lib_test.py
    ├─/NI9205
    │  ├─__init__.py
    │  ├─device.py (??)
    │  └─NI9205_read_channel.py
    ├─/NI9217
    │  ├─__init__.py
    │  ├─device.py (??)
    │  └─NI9217_read_channel.py
    ├─/dialogPerformMeasurement
    │  ├─__init__.py
    │  └─performMeasurement_v1.py (??)
    └─/dialogSaveData
       ├─__init__.py
       └─saveDataDialog_v1.py (??)
```

4. Conclusion

We propose a simple measurement setup controlled from computer running a python script based on open-source libraries. The measurement setup outperforms high-power 4-quadrant measurement systems, such as Keithley 2651A, in measurements in I. and IV. quadrant.

The measurement setup performs IV measurements, with special attention to characterization of reverse-bias region in IV. quadrant. Testing within this quadrant requires safety measures, such that the avalanche-breakdown does not cause permanent damage to the tested PV cell.

Despite the specificity of the IV measurements, we provide tested and well-commented source code for connecting multiple devices from various manufacturers to single computer over USB. This is especially interesting for connected National Instrument measurement card(s), which notoriously lack documentation support and are generally controllable by proprietary software only, such as LabView.

Therefore, we believe that researchers testing PV cells and PV devices as well as researchers coordinating multiple laboratory devices from a single PC will find this work interesting and useful.

References