Version 1.0

SOLIS-Sourcemeter: User Manual for Keithley 2636A Current-Voltage Characterization Software

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1 Introduction

This software was developed as a deliverable of the MSCA Staff Exchange Project SOLIS (https://cordis.europa.eu/project/id/101183049). SOLIS-Sourcemeter is a measurement suite for electrical characterization of semiconductor devices using the Keithley 2636A dual-channel SourceMeter. The software supports three primary measurement modes: diode/photovoltaic characterization, transistor characterization, and neuromorphic synapse measurements. All measurements utilize buffered acquisition for speed and reliability.

1.1 Supported Connection Types

- GPIB (IEEE-488)
- RS232 (Serial)
- LAN (TCP/IP)

1.2 Key Features

- Real-time JV curve plotting with dual-axis power density display
- Automatic photovoltaic parameter extraction (V_{oc}, J_{sc}, FF, PCE)
- Semi-logarithmic current visualization
- Hysteresis characterization for ferroelectric and memristive devices
- Advanced synapse characterization: SRDP, STDP, cycling endurance
- Multi-device sequential testing
- Hardware-free simulation mode for protocol development

2 Diode Mode: Photovoltaic and Rectifier Characterization

2.1 Measurement Principle

The software performs voltage-sweep current measurements to generate current density vs. voltage (JV) curves. For photovoltaic devices under illumination, the software automatically calculates standard solar cell parameters.

2.2 Configuration Parameters

Parameter	Description	Typical Range
Starting Voltage	Initial sweep voltage	-0.5 to 0 V
Ending Voltage	Final sweep voltage	0.8 to 1.2 V
Voltage Step	Voltage increment	0.01 to 0.05 V
NPLC	Integration time (power line cycles)	0.01 to 10
Compliance	Current limit	1 nA to 1.5 A
Surface Area	Active device area	0.01 to 10 cm^2
Irradiance	Incident light intensity	100 to 1000 W/m^2

Table 1: Diode mode configuration parameters

2.3 Photovoltaic Parameter Extraction

For illuminated measurements, the software calculates:

1. **Open-Circuit Voltage (V_{oc}):** Interpolated voltage where $J = 0$

$$V_{oc} = V_{\text{low}} - J_{\text{low}} \frac{V_{\text{high}} - V_{\text{low}}}{J_{\text{high}} - J_{\text{low}}} \tag{1}$$

2. **Short-Circuit Current Density (J_{sc}):** Current density at $V = 0$

$$J_{sc} = -J(V = 0) \quad [\text{mA/cm}^2] \tag{2}$$

3. **Fill Factor (FF):** Ratio of maximum power to theoretical maximum

$$\text{FF} = \frac{|V_{mp} \cdot J_{mp}|}{V_{oc} \cdot J_{sc}} \times 100\% \tag{3}$$

4. **Power Conversion Efficiency (PCE):**

$$\text{PCE} = \frac{|P_{max}|}{P_{\text{incident}}} \times 100\% = \frac{|V_{mp} \cdot J_{mp}|}{P_{\text{incident}}} \times 100\% \tag{4}$$

where P_{incident} is the irradiance in mW/cm^2.

2.4 Hysteresis Measurement

Enable hysteresis measurement to characterize voltage-dependent polarization or ion migration effects. The software performs forward and reverse voltage sweeps for the specified number of cycles. This is important mostly for:

- Perovskite solar cells (ion migration)
- Ferroelectric devices
- Memristive systems

2.5 Dark vs. Illuminated Measurements

Dark JV: Characterizes diode properties without photogeneration. The software does not include fitting yet. Use for:

- Ideality factor determination
- Reverse saturation current extraction
- Shunt and series resistance analysis

Illuminated JV: Measures photovoltaic performance. Ensure accurate calibration of whatever light source you use for precise PCE calculation.

3 Transistor Mode: Field-Effect Characterization

3.1 Measurement Protocol

Transistor mode performs output characteristics (I_D-V_{DS}) measurements at multiple gate voltages (V_{GS}). The software sweeps drain-source voltage while incrementally stepping the gate voltage, generating a family of curves.

3.2 Channel Configuration

The selected channel controls V_{DS} (drain-source), while the opposite channel controls V_{GS} (gate-source):

- **Channel A selected:** SMU A = drain, SMU B = gate
- **Channel B selected:** SMU B = drain, SMU A = gate

3.3 Parameter Extraction

From the output characteristics, extract:

- **Linear regime:** Mobility, threshold voltage
- **Saturation regime:** On/off ratio, subthreshold swing
- **Contact resistance:** From low V_{DS} behavior

3.4 Data Export Format

The CSV file contains columns for each V_{GS} value with paired voltage-current density data. Surface area is embedded in the header for conductivity calculations.

4 Synapse Mode: Neuromorphic Device Characterization

Synapse mode implements pulse-read sequences for characterizing artificial synapses and memristive devices. The software supports basic potentiation/depression measurements as well as the more advanced plasticity protocols.

4.1 Basic Synapse Measurement

4.1.1 Pulse-Read Sequence

The fundamental operation sequence is:

1. Apply stimulus pulse (voltage or current) on stimulus channel
2. Wait for pulse duration (t_{width})
3. Turn off stimulus
4. Wait for read delay (t_{delay})
5. Apply read voltage on read channel
6. Measure current after settling time
7. Calculate conductance: $G = I/V_{\text{read}}$
8. Return to idle state
9. Wait for period completion

4.1.2 Timing Parameters

Parameter	Description	Typical Range
Stim Width	Pulse duration	10 to 1000 ms
Stim Period	Time between pulses	50 to 2000 ms
Read Delay	Post-pulse settling time	5 to 100 ms
Settle Time	Measurement stabilization	2 to 20 ms

Table 2: Synapse timing parameters

Critical constraint:

$$t_{\text{period}} \geq t_{\text{width}} + t_{\text{delay}} + t_{\text{settle}} + t_{\text{measurement}} \tag{5}$$

4.1.3 Drive Types

- **Voltage-driven (V):** Apply fixed voltage, measure current
- **Current-driven (I):** Apply fixed current, measure voltage

Voltage drive is preferred for most memristive devices; current drive is suitable for phase-change memory (PCM) characterization, which is not part of the SOLIS project.

4.1.4 Synapse Metrics

The software calculates:

- **Paired-Pulse Facilitation (PPF):**

$$\text{PPF} = \frac{G_2}{G_1} \times 100\% \tag{6}$$

  Measures short-term plasticity; critical for temporal information processing.
- **Conductance Change (ΔG):**

$$\Delta G = G_{\text{final}} - G_{\text{initial}} \tag{7}$$

$$\Delta G_{\%} = \frac{G_{\text{final}} - G_{\text{initial}}}{G_{\text{initial}}} \times 100\% \tag{8}$$

- **Dynamic Range:** $G_{\text{max}}/G_{\text{min}}$ ratio (on/off ratio)

4.2 Presets for Common Protocols

Preset	Voltage	Width	Period	Pulses
LTP Moderate	+1.0 V	100 ms	200 ms	50
LTD Moderate	−1.0 V	100 ms	200 ms	50
PPF Test	+1.5 V	10 ms	30 ms	2
High Speed	+1.0 V	10 ms	20 ms	100

Table 3: Preset configurations for basic synapse measurements

4.3 Spike-Rate-Dependent Plasticity (SRDP)

SRDP characterizes how synaptic weight change depends on input spike frequency which is a critical property for rate-coded neural networks.

4.3.1 Measurement Protocol

The software sweeps through user-defined frequencies, applying a fixed number of pulses at each frequency and measuring the resulting ΔG.

$$f_i = \begin{cases} \text{Logarithmic:} & 10^{\log_{10}(f_{\text{min}}) + i \cdot \frac{\log_{10}(f_{\text{max}}) - \log_{10}(f_{\text{min}})}{N-1}} \\ \text{Linear:} & f_{\text{min}} + i \cdot \frac{f_{\text{max}} - f_{\text{min}}}{N-1} \end{cases} \tag{9}$$

where $i \in [0, N-1]$ and N is the number of frequency points.

4.3.2 SRDP Parameters

- **Freq Start:** Minimum frequency (1-100 Hz typical)
- **Freq End:** Maximum frequency (10-1000 Hz typical)
- **Freq Points:** Number of frequencies to test (5-20 recommended)
- **Log Scale:** Logarithmic spacing (recommended for wide frequency ranges)

4.3.3 Data Interpretation

Plot ΔG vs. frequency to identify:

- **Potentiation regime:** Positive ΔG increasing with frequency
- **Depression regime:** Negative ΔG magnitude increasing with frequency
- **Saturation:** Plateau at high frequencies
- **Critical frequency:** Transition point between LTD and LTP

4.4 Spike-Timing-Dependent Plasticity (STDP)

STDP characterizes synaptic weight change as a function of relative timing between pre- and post-synaptic spikes, and it is the fundamental learning rule in temporal coding.

4.4.1 Timing Convention

$$\Delta t = t_{\text{pre}} - t_{\text{post}} \tag{10}$$

- $\Delta t > 0$: Pre-synaptic spike precedes post-synaptic $\rightarrow$ **LTP** (potentiation)
- $\Delta t < 0$: Post-synaptic spike precedes pre-synaptic $\rightarrow$ **LTD** (depression)

4.4.2 Implementation

For each Δt value:

1. Measure initial conductance G_0
2. Apply N spike pairs with timing offset Δt
3. Measure final conductance G_f
4. Calculate $\Delta G = G_f - G_0$

The stimulus channel delivers pre-synaptic spikes; the read channel delivers post-synaptic spikes.

4.4.3 STDP Parameters

- Δt **Start:** Minimum timing offset (typically -50 ms)
- Δt **End:** Maximum timing offset (typically $+50$ ms)
- Δt **Points:** Number of timing points (10-20 recommended)
- **Spike Pairs:** Number of paired spikes per timing point (20-100)
- **Pre-spike Level:** Pre-synaptic pulse amplitude
- **Post-spike Level:** Post-synaptic pulse amplitude
- **Pair Period:** Time between consecutive spike pairs

4.4.4 Expected STDP Window

Classic STDP follows exponential decay:

$$\Delta G(\Delta t) = \begin{cases} A_+ \exp\left(-\frac{\Delta t}{\tau_+}\right) & \Delta t > 0 \quad \text{(LTP)} \\ -A_- \exp\left(\frac{\Delta t}{\tau_-}\right) & \Delta t < 0 \quad \text{(LTD)} \end{cases} \tag{11}$$

where A_+, A_- are amplitudes and τ_+, τ_- are time constants (typically 10-20 ms).

4.5 Potentiation-Depression Cycling

Cycling characterization assesses device endurance and reproducibility by alternating potentiation and depression phases.

4.5.1 Cycle Structure

Each cycle consists of:

1. **Potentiation phase:** Apply positive stimulus sequence
2. **Depression phase:** Apply negative stimulus sequence
3. **Inter-cycle delay:** Recovery time before next cycle

4.5.2 Independent Parameter Control

Potentiation and depression phases use separate parameter sets, allowing asymmetric characterization:

- Different pulse amplitudes (e.g., +1.5 V pot, −1.0 V dep)
- Different pulse widths (e.g., 50 ms pot, 100 ms dep)
- Different number of pulses
- Different read voltages (e.g., 0.15 V pot, 0.08 V dep)

4.5.3 Cycle Presets

Preset	Cycles	Pot/Dep	Inter-cycle	Application
Standard Cycle	5	±1.0 V	1000 ms	Balanced protocol
Fast Cycle	10	±1.2 V	500 ms	Rapid screening
High Endurance	20	±0.8 V	2000 ms	Long-term stability
Asymmetric	5	$+1.5/-1.0$ V	1500 ms	Unbalanced dynamics

Table 4: Cycle preset configurations

4.5.4 Cycle Metrics

The software calculates:

- **Mean ΔG (potentiation):** Average potentiation across cycles
- **Mean ΔG (depression):** Average depression across cycles
- **Reproducibility (CV):** Coefficient of variation

$$\mathrm{CV} = \frac{\sigma(\Delta G)}{|\mu(\Delta G)|} \times 100\% \tag{12}$$

  Lower CV indicates better reproducibility.
- **Dynamic Range:**

$$\Delta G_{\mathrm{range}} = \langle G_{\mathrm{pot,final}} \rangle - \langle G_{\mathrm{dep,final}} \rangle \tag{13}$$

- **On/Off Ratio:**

$$\mathrm{On/Off} = \frac{\langle G_{\mathrm{pot,final}} \rangle}{\langle G_{\mathrm{dep,final}} \rangle} \tag{14}$$

4.5.5 Real-Time Plotting

The software provides real-time plot updates during cycling, allowing immediate observation of:

- Cycle-to-cycle variability
- Fatigue effects (degradation over cycles)
- Asymmetric behavior between potentiation and depression

4.6 Multi-Device Sequential Testing

Multi-device mode enables automated characterization of multiple devices without manual intervention.

4.6.1 Configuration

- **Number of Devices:** Total devices to test (2-20 typical)
- **Device Name Pattern:** Base identifier (e.g., "Device" generates Device_1, Device_2, ...)
- **Inter-device Delay:** Recovery time between devices (1-5 seconds)

All devices use the same cycle parameters (potentiation, depression, number of cycles).

4.6.2 Multi-Device Workflow

1. Configure cycle parameters
2. Enable multi-device mode
3. Set device count and naming
4. Run measurement
5. Software sequentially tests each device
6. Aggregated results display device-to-device variability

4.6.3 Statistical Analysis

Multi-device measurements enable:

- Device-to-device variability assessment
- Fabrication yield estimation
- Statistical reliability metrics
- Outlier identification

It is better used with a multiplexer on a synaptic network for example.

5 Simulation Mode

Simulation mode allows protocol development and testing without hardware connection. Enable via the "Simulate (No Hardware)" checkbox in Synapse mode. I made it at first to test the logic without having to connect the hardware, but it can also be useful to help designing experimental protocols.

5.1 Simulation Models

- **Basic Synapse:** Exponential conductance change with learning rate

$$G_{n+1} = G_n + (G_{\text{target}} - G_n) \times \alpha \tag{15}$$

  where $\alpha = 0.05$ (5% step size).
- **SRDP:** Logarithmic frequency dependence

$$\Delta G_{\text{norm}}(f) = \frac{\log_{10}(f+1)}{\log_{10}(100)} \times A \tag{16}$$

- **STDP:** Exponential timing window

$$\Delta G(\Delta t) = \begin{cases} 0.5 \exp(-\Delta t/20 \text{ ms}) & \Delta t > 0 \\ -0.3 \exp(\Delta t/20 \text{ ms}) & \Delta t < 0 \end{cases} \tag{17}$$

All simulations include Gaussian noise (±2%-5%) to approximate realistic behavior.

6 Measurement Optimization

6.1 NPLC Selection

Number of Power Line Cycles (NPLC) controls integration time and noise rejection:

NPLC	Integration Time	Application
0.01	~ 0.17 ms	Fast sweep, low noise
0.1	~ 1.7 ms	Synapse read, moderate noise
1.0	~ 17 ms	High-precision DC measurements
10	~ 170 ms	Ultra-low noise, slow sweep

Table 5: NPLC selection guide (60 Hz power line)

Trade-off: Higher NPLC improves signal-to-noise ratio but increases measurement time.

6.2 Autorange vs. Fixed Range

- **Autorange:** Instrument automatically selects current range. Use for wide current range devices or initial characterization. Increases measurement time by $\sim$ 2-5×.
- **Fixed Range:** Manual range selection. Use for well-characterized devices with known current levels. Fastest measurement speed.

6.3 4-Wire vs. 2-Wire Sensing

- **4-Wire (Kelvin):** Eliminates lead resistance. Essential for low-resistance devices ($<$ 100 Ω) and high-current measurements.
- **2-Wire:** Simpler configuration. Acceptable for high-resistance devices ($>$ 10 kΩ) where lead resistance is negligible.

6.4 Compliance Settings

Current compliance prevents device damage during voltage sourcing:

$$I_{\text{compliance}} \geq I_{\text{expected,max}} \times 1.2 \tag{18}$$

Set compliance 20% above expected maximum current. For current sourcing, set voltage compliance 20% above expected voltage.

6.5 Timeout Configuration

Timeout prevents software lockup during long measurements:

$$t_{\text{timeout}} = N_{\text{points}} \times \text{NPLC} \times \frac{1}{f_{\text{line}}} \times 3 \tag{19}$$

The software automatically calculates timeout with 3× safety margin. Increase timeout manually for autorange or complex sequences.

7 Data Export and Analysis

7.1 CSV File Structure

7.1.1 Diode Mode

Headers contain:

- Sample name (Cell #) with irradiance
- Surface area

Data columns:

- Voltage (V)
- Current Density (mA/cm^2)

Multiple measurements are stored in adjacent column pairs.

7.1.2 Synapse Mode

Metadata header (lines starting with `#`) contains all measurement parameters.
Data columns:

- **pulse:** Pulse index
- **timestamp_s:** Relative time in seconds
- **I_A:** Measured current in amperes
- **V_read_V:** Read voltage
- **conductance_S:** Calculated conductance in siemens

7.1.3 Cycle Characterization

Additional columns:

- **cycle:** Cycle number
- **phase:** "potentiation" or "depression"

Summary metrics are embedded in the metadata header.

7.1.4 Multi-Device Data

Additional column:

- **device:** Device identifier

All devices are stored in a single CSV file for easy comparison.

7.2 Extracting Metadata

Python example for metadata extraction:

```
import re

def extract_metadata(csv_path):
    metadata = {}
    with open(csv_path, 'r') as f:
        for line in f:
            if not line.startswith('#'):
                break
            params = re.findall(r'(\w+)=([\d.eE+-]+)', line)
            metadata.update(params)
    return metadata
```

8 Contact and Support

For questions, bug reports, or feature requests:

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