Version 1.0

Experimental Setup Guidelines for Artificial Visual Synapse Characterisation

SOLIS Project - Work Package 1

SOLIS Consortium

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Abstract

This document is addressed to Photovoltaic (PV) researchers interested to investigate their devices for visual synapses and neuromorphic applications. It is written as part of the Marie Curie Staff Exchange project SOLIS `https://cordis.europa.eu/project/id/101183049`. The document provides guidelines for establishing an experimental platform to characterise artificial visual synapses using optical stimulation. Designed for thin film photovoltaic researchers, it covers hardware configurations, synchronisation strategies, and standardized measurement protocols for synaptic plasticity characterisation.

Contents

1 Introduction

Visual synapses operate through optically-controlled memristive behavior, leveraging persistent photoconductivity in thin film semiconductors. Characterisation requires:

- Pulsed optical stimulation (write operation)
- Electrical conductance readout (read operation)
- Precise temporal control (ms to s timescales)
- Synchronized triggering between stimulation and measurement

This guide addresses two primary hardware configurations: dual-channel Source meter units (e.g., Keithley 2636A) and combined waveform generator + measurement instrument setups.

2 Hardware Configurations

2.1 Configuration A: Dual-Channel Source meter (Keithley 2636A)

Required equipment:

- Keithley 2636A (or equivalent dual-channel SMU)
- Fiber-coupled LED with driver
- LED driver with external trigger capability
- Optical fiber and collimator
- Calibrated optical power meter

Connection scheme:

- **Channel A:** Device terminals (apply read voltage, measure current)
- **Channel B:** LED driver trigger input (pulse generation)
- **Optical path:** LED → fiber → collimator → device

Advantages: Integrated control, high timing precision, simplified synchronisation via software.

2.2 Configuration B: Waveform Generator + Measurement Instrument

Required equipment:

- Dual-channel waveform generator (e.g., Multicomp Pro MP751062)
- Digital multimeter with trigger input (e.g., Keysight 34460A) or single-channel SMU
- Fiber-coupled LED with triggered driver (e.g., Thorlabs LEDD1B + M430F1)
- Multimode optical fiber and collimator
- Calibrated optical power meter

Connection scheme:

- **WFG Channel 1:** LED driver external trigger input (optical stimulation pulses)
- **WFG Channel 2:** Device bias (apply read voltage V_{read})
- **DMM input:** Device current measurement
- **Trigger synchronisation:** WFG output → DMM external trigger input

Critical consideration: The measurement instrument must support external triggering to synchronize current acquisition with the pulse sequence.

2.3 Budget-Conscious Example Setup (∼€2,350)

Component	Model/Specs	Cost (€)
Waveform generator	Multicomp Pro MP751062 (2-ch, 60 MHz)	250
Digital multimeter	Keysight 34460A (6.5-digit, triggerable)	1,300
Fiber-coupled LED	Thorlabs M430F1 (430 nm, 5.3 mW)	250
LED driver	Thorlabs LEDD1B (T-Cube, ext. trigger)	350
Optical components	Fiber + collimator	200
Total		**2,350**

Table 1: Low-cost experimental setup for visual synapse characterisation

Note: Multiple LEDs at different wavelengths are recommended to study spectral response.

3 Optical Calibration

3.1 Power Calibration Protocol

Accurate characterisation requires calibrated incident optical power density at the device surface.

Procedure:

1. Position optical power meter detector at device plane.
2. Measure optical power P_{opt} [mW] for each LED at operating current.
3. Calculate power density: $P_d = P_{\text{opt}}/A_{\text{beam}}$ [mW cm^{-2}]
4. Record beam diameter at device position (measure spot size with beam profiler or imaging).
5. Verify spatial uniformity across device active area.

Requirements:

- Calibrated Si or InGaAs photodiode detector (wavelength-dependent)
- Power meter with nW to mW range
- Document: λ, P_{opt}, A_{beam}, LED current, measurement distance

4 Timing and Synchronisation

4.1 Temporal Parameters

Synaptic characterisation in thin film device should happen on timescales from milliseconds to seconds. Ideally we would go faster, but for the equipment described here, this is the fastest we can hope for:

$$T_{\text{period}} \geq t_{\text{pulse}} + t_{\text{delay}} + t_{\text{settle}} + t_{\text{meas}} \tag{1}$$

$$t_{\text{pulse}} : \text{optical stimulation duration (10–1000 ms)} \tag{2}$$

$$t_{\text{delay}} : \text{post-pulse relaxation (5–100 ms)} \tag{3}$$

$$t_{\text{settle}} : \text{measurement stabilization (2–20 ms)} \tag{4}$$

$$t_{\text{meas}} : \text{current acquisition window (1–50 ms)} \tag{5}$$

4.2 Configuration A: Keithley 2636A Synchronisation

Synchronisation is managed internally via the controlling software:

1. Channel B outputs voltage pulse to trigger LED driver.
2. Software waits $t_{\text{pulse}} + t_{\text{delay}}$.

3. Channel A applies V_{read}, waits t_{settle}.
4. Channel A measures current.
5. Software calculates conductance: $G = I/V_{\text{read}}$.

NPLC setting: Use NPLC = 0.1–1 for balance between speed and noise rejection (see Section 5).

4.3 Configuration B: External Triggering

Requires explicit hardware synchronisation:

Setup:

1. WFG Channel 1 generates optical stimulus trigger (TTL pulse, duration t_{pulse}).
2. WFG Channel 2 applies constant V_{read} to device during read phase.
3. DMM external trigger configured to start acquisition at $t = t_{\text{pulse}} + t_{\text{delay}}$.
4. Trigger signal: use WFG marker output or delayed copy of Channel 1 pulse.

Critical: Verify DMM trigger latency (typically 1–5 ms). Adjust t_{delay} accordingly.

Measurement sequence:

```
for each pulse:
    t=0:     WFG Ch1 triggers LED (ON for t_pulse)
    t=t_pulse: LED turns OFF
    t=t_pulse + t_delay: WFG triggers DMM acquisition
    t=t_pulse + t_delay + t_settle: DMM samples current
    Record I, calculate G = I / V_read
```

4.4 Instrument Speed Considerations

- **WFG:** Typical trigger jitter < 1 µs, adequate for ms-scale pulses.
- **DMM (e.g., Keysight 34460A):** Integration time depends on NPLC; trigger delay ~2 ms. Use fast trigger mode if available.
- **Keithley 2636A:** Buffer-based acquisition with ~17 ms per point at NPLC=1 (60 Hz line frequency). Use lower NPLC for faster measurements. However, from my experience, it is better to limit yourself to about 30ms unless you operate at very high read voltages so the current is high, often above 0.5V in our devices.
- **LED driver:** Rise/fall time typically < 1 µs. Verify driver specifications but it is normally not a limitation.

5 Integration Time and Noise (NPLC)

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

NPLC	Integration Time (60 Hz)	Application
0.01	0.17 ms	Fast transients, high noise
0.1	1.7 ms	Synapse readout, moderate noise
1.0	17 ms	Standard DC measurements
10	170 ms	Ultra-low noise, slow dynamics

Table 2: NPLC selection guidelines

Recommendation: For synaptic characterisation with $t_{\text{pulse}} \geq 10$ ms, use NPLC = 0.1–1.

6 Standard Characterisation Protocols

6.1 General Measurement Sequence

All protocols follow this base structure:

1. **Initialize:** Measure baseline conductance G_0 (zero illumination). Ensure that the baseline is almost flat at the chosen read voltage, to make sure that the read voltage does not significantly contribute to the plasticity.
2. **Stimulate:** Apply optical pulse sequence.
3. **Read:** Measure conductance after each pulse: apply V_{read}, measure I, compute $G = I/V_{\text{read}}$.
4. **analyse:** Calculate plasticity metrics (see equations below).

Read voltage: We recommend to use $V_{\text{read}} = 0.05$–0.2 V (non-destructive, linear regime). Verify device IV characteristics first, and as previoulsy said, be sure that it does not significantly contribute to the plasticity.

6.2 Long-Term Potentiation (LTP)

Objective: Demonstrate sustained conductance increase under repeated optical stimulation.

Protocol:

1. Measure G_0 (initial conductance, dark conditions).
2. Apply $N = 50$–200 optical pulses:
   - Pulse intensity: $P_d = 1$–$10\ \text{mW}\,\text{cm}^{-2}$
   - Pulse width: $t_{\text{pulse}} = 50$–500 ms
   - Period: $T = 200$–1000 ms
3. After each pulse: wait t_{delay}, measure G_n.
4. Plot G_n vs. pulse number n.

Metrics:

$$\Delta G_{\text{LTP}} = G_N - G_0 \tag{6}$$

$$\Delta G_{\%} = \frac{G_N - G_0}{G_0} \times 100\% \tag{7}$$

Expected behavior: G_n increases and saturates at $G_{\max}$.

6.3 Long-Term Depression (LTD)

Objective: Demonstrate conductance decrease. It often requires reverse bias or dark relaxation, but in some cases, we have observed depression assisted by light (which is ideal, as you then have a fully optically controlled synapse).

Protocol (dark relaxation):

1. Potentiate device to $G_{\max}$ (apply LTP sequence).
2. Measure conductance decay in dark: sample $G(t)$ at intervals (e.g., every 10 s for 10 min).
3. Fit decay: $G(t) = G_\infty + (G_{\max} - G_\infty)e^{-t/\tau}$

Protocol (electrical reset):

1. After LTP, apply negative voltage pulses (if applicable) or opposite polarity.
2. Monitor G_n decrease over M reset pulses.

Metrics:

$$\Delta G_{\text{LTD}} = G_0 - G_M \tag{8}$$

$$\tau : \text{decay time constant} \tag{9}$$

6.4 Short-Term Plasticity: Paired-Pulse Facilitation (PPF)

Objective: Measure conductance enhancement from closely-spaced pulse pairs.

Protocol:

1. Apply two identical optical pulses separated by interval $\Delta t = 10$–100 ms.
2. Measure G_1 after first pulse, G_2 after second pulse.
3. Repeat for multiple Δt values (e.g., 10, 20, 50, 100 ms).
4. Allow relaxation between trials ($\sim$60 s in dark).

Metrics:

$$\text{PPF}(\Delta t) = \frac{G_2}{G_1} \times 100\% \tag{10}$$

Expected behavior: PPF $> 100\%$ for $\Delta t < \tau_{\text{relax}}$, where τ_{relax} is the conductance relaxation time constant.

6.5 Spike-Rate-Dependent Plasticity (SRDP)

Objective: Characterise synaptic weight change as a function of input frequency.

Protocol:

1. Define frequency range: $f_{\text{min}} = 1$–10 Hz, $f_{\text{max}} = 50$–500 Hz.
2. Use $N_f = 8$–15 logarithmically-spaced frequencies:

$$f_i = f_{\text{min}} \cdot \left(\frac{f_{\text{max}}}{f_{\text{min}}}\right)^{i/(N_f-1)}, \quad i = 0, \ldots, N_f - 1 \tag{11}$$

3. At each f_i:
   - Measure G_0.
   - Apply $N_{\text{pulse}} = 30$–100 pulses at frequency f_i (period $T = 1/f_i$).
   - Measure final conductance G_f.
   - Calculate $\Delta G(f_i) = G_f - G_0$.
   - Allow full relaxation (5–10 min dark) before next frequency.
4. Plot ΔG vs. f.

Typical pulse parameters:

- $t_{\text{pulse}} = 10$–50 ms (constrain: $t_{\text{pulse}} < T/2$)
- Fixed intensity across all frequencies

Expected behavior: ΔG increases with f (potentiation regime) or decreases (depression regime), possibly showing critical frequency transition.

6.6 Spike-Timing-Dependent Plasticity (STDP)

Objective: Map synaptic weight change as a function of pre-post spike timing. This can be hard to do in a fully optical setup. Below is a proposition for a protocol.

Protocol:

1. Define timing offset range: $\Delta t \in [-50, +50]$ ms (10–20 points).
2. At each Δt_j:
   - Measure G_0.
   - Apply $N_{\text{pairs}} = 30$–100 spike pairs:
     - **Pre-synaptic spike:** Optical pulse ($t_{\text{pulse}} = 10$–20 ms)
     - **Post-synaptic spike:** Electrical pulse on device (e.g., +0.5 V, 10 ms) applied at time $t + \Delta t_j$
     - *Configuration A:* Channel A applies post-spike, Channel B triggers LED for pre-spike.
     - *Configuration B:* WFG Ch1 triggers LED (pre), WFG Ch2 applies voltage pulse (post) with programmed delay.

- Inter-pair period: $T_{\text{pair}} = 200$–500 ms.
- Measure G_f, calculate $\Delta G(\Delta t_j) = G_f - G_0$.
- Allow relaxation before next Δt.

3. Plot ΔG vs. Δt.

Timing convention:

$$\Delta t = t_{\text{pre}} - t_{\text{post}} \tag{12}$$

- $\Delta t > 0$: Pre before post $\rightarrow$ expected LTP (potentiation)
- $\Delta t < 0$: Post before pre $\rightarrow$ expected LTD (depression)

Expected STDP window:

$$\Delta G(\Delta t) = \begin{cases} A_+ \exp(-\Delta t/\tau_+) & \Delta t > 0 \\ -A_- \exp(\Delta t/\tau_-) & \Delta t < 0 \end{cases} \tag{13}$$

where $\tau_\pm \approx 10$–20 ms (biological inspiration).

6.7 Current-Voltage (JV) Hysteresis

Objective: Characterise memristive behavior in the device electrical response.

Protocol:

1. **Dark sweep:**
   - Sweep voltage: $V = -0.2$ to $+1.0$ V (forward), then reverse (backward).
   - Step size: $\Delta V = 10$–20 mV.
   - Measure current at each point.
2. **Illuminated sweep:**
   - Apply constant illumination ($P_d = 1$–$10\ \text{mW cm}^{-2}$).
   - Repeat forward-backward voltage sweep.
3. **Light-soaking effect:**
   - Pre-illuminate device (e.g., 60 s at $10\ \text{mW cm}^{-2}$).
   - Immediately measure dark JV curve.
   - Compare with initial dark JV (measure hysteresis width).

Analysis:

- Hysteresis area: $A_{\text{hyst}} = \oint I\, dV$
- Shift in turn-on voltage or resistance state between forward/backward sweeps
- Persistence of conductance change after light removal

7 Data Acquisition and Analysis

7.1 Data Structure

Record for each measurement:

- Time stamp (relative to sequence start)
- Pulse index n
- Measured current I [A]
- Applied read voltage V_{read} [V]
- Calculated conductance $G = I/V_{\text{read}}$ [S]
- Optical parameters: λ, P_d, t_{pulse}
- Environmental conditions: temperature, ambient light (if not in dark box)

Metadata: Device ID, area, materials, measurement date, protocol parameters.

Metric	Definition	Interpretation
ΔG	$G_f - G_i$	Absolute conductance change
$\Delta G_{\%}$	$(G_f - G_i)/G_i \times 100\%$	Relative change
Dynamic range	$G_{\max}/G_{\min}$	On/off ratio
PPF	$G_2/G_1 \times 100\%$	Short-term facilitation
Nonlinearity	Deviation from linear $G(n)$	Synaptic update symmetry

Table 3: Synaptic plasticity metrics

7.2 Key Metrics

7.3 Typical Results

LTP: Expect $\Delta G > 20$–100% over 50–200 pulses. Saturation indicates $G_{\max}$ reached.

SRDP: Logarithmic or sigmoidal $\Delta G(f)$ relationship. Critical frequency f_c marks LTD-to-LTP transition.

STDP: Asymmetric window with $\Delta G > 0$ for $\Delta t > 0$ and $\Delta G < 0$ for $\Delta t < 0$. Time constants $\tau_{\pm} = 10$–50 ms typical.

JV Hysteresis: Pinched loop at origin indicates memristive behavior. Hysteresis width correlates with memory retention.

8 Experimental Best Practices

8.1 Device Considerations

- **Compliance:** Set current compliance 20% above expected maximum to prevent device damage.
- **Bias polarity:** Verify device polarity (some devices require specific bias direction for potentiation).
- **Active area:** Define and document device illuminated area for power density calculations.
- **4-wire vs. 2-wire:** Use 4-wire (Kelvin) sensing for low-resistance devices ($< 100\ \Omega$).

8.2 Environmental Control

- **Dark box:** Essential. Eliminate ambient light during measurements.
- **Temperature:** Ideally it should be monitored and stable, as we are measuring very small currents. Ideally...
- **Humidity:** Can be important for air-sensitive materials, but has not been an issue for us so far.

Measurement quality

- **Repeatability:** We should try to perform measurements per protocol and report mean ± standard deviation. But some devices may degrade.
- **Relaxation time:** Allow sufficient dark recovery between measurements (typically 5–10 min) to avoid cumulative effects. If you have a way to reset the device, optically or electrically, even better.
- **Baseline stability:** Verify G_0 returns to initial value after relaxation. If not, device may show fatigue or irreversible damages.
- **Cable shielding:** If doing very low current measurements, we recommend shielded coaxial cables to minimise electromagnetic interference.

9 Software Integration

In the frame of the project SOLIS, we developped the SOLIS control software (see separate User Manual, SOLIS-Sourcemeter v1.0) which implements these protocols for Keithley 2636A systems. For Configuration B setups, adapt the software control logic:

Required modifications:

- Replace Keithley VISA commands with WFG-specific commands (SCPI standard for most instruments).
- Implement external triggering: send trigger signal to DMM after $t_{\text{pulse}} + t_{\text{delay}}$.
- Read current from DMM via VISA/GPIB/USB after each trigger.
- Calculate conductance: $G = I_{\text{DMM}}/V_{\text{read, WFG}}$.

Example Python pseudocode (Configuration B):

```
import pyvisa
rm = pyvisa.ResourceManager()
wfg = rm.open_resource('USB::0x1234::0x5678::INSTR')  # WFG address
dmm = rm.open_resource('USB::0xABCD::0xEF01::INSTR')  # DMM address

# Configure WFG
wfg.write('SOURce1:FUNCtion PULSE')  # Ch1: LED trigger
wfg.write(f'SOURce1:PULSe:WIDTh {t_pulse}')
wfg.write(f'SOURce1:VOLTage:HIGH 3.3')  # TTL level
wfg.write('SOURce2:VOLTage:LEVel {V_read}')  # Ch2: read voltage

# Configure DMM
dmm.write('TRIGger:SOURce EXTernal')
dmm.write(f'TRIGger:DELay {t_delay + t_settle}')

for n in range(N_pulses):
    wfg.write('TRIGger')  # Trigger WFG (outputs Ch1 pulse, maintains Ch2)
    dmm.write('INITiate')  # Arm DMM for triggered measurement
    I = float(dmm.query('FETCh?'))  # Read current
    G = I / V_read
    # Store data: n, I, G
    time.sleep(T_period)  # Wait for next pulse
```

10 Summary and Recommendations

10.1 Minimum Equipment Requirements

- **Configuration A:** Dual-channel SMU (e.g., Keithley 2636A), fiber-coupled LED, triggered driver, optical components. Cost: ∼€15,000.
- **Configuration B:** Dual-channel WFG, triggerable DMM, fiber-coupled LED, triggered driver, optical components. Cost: ∼€2,350.
- **Custom-made** At UPC, we use a more advanced sourcemeter (Keysight B1500A) which costs an arm and a leg, but permits timescales of ns and a current resolution of 10nA. The University of Liverpool also has a custom setup.

10.2 Critical Success Factors

1. **Optical calibration:** Accurate P_d measurement is essential for reproducibility. Really be sure that you know your incident power.

2. **Timing synchronisation:** Verify trigger delays and instrument response times. You don't want the measure to occur after the read voltage pulse, for example. We recommend starting slow, and progressively increasing the speed (e.g. decreasing the timescales).
3. **NPLC optimization:** Balance measurement speed vs. noise based on device dynamics.
4. **Environmental stability:** Dark box is really essential, and maybe temperature/humidity control, shielded cables.
5. **Systematic protocols:** As much as possible, we should try to follow standardised sequences for cross-lab comparisons.

10.3 Recommended Workflow

1. **Initial characterisation:** Dark and illuminated JV curves to identify memristive behavior and select V_{read}.
2. **Basic plasticity:** LTP/LTD to verify synaptic response and determine optimal pulse parameters.
3. **Advanced protocols:** PPF, SRDP, STDP to fully characterise plasticity functions.
4. **Wavelength dependence:** Repeat key protocols with multiple LEDs (if device is wavelength-selective).
5. **Endurance testing:** Potentiation-depression cycling (100–1000 cycles) for stability assessment.

11 Conclusion

This guide provides a practical framework specifically addressed to thin film PV researchers to establish visual synapse characterisation capabilities using accessible equipment. The described protocols form a standardised basis for comparing results across the SOLIS consortium and the broader research community.

For detailed software implementation, refer to the *Source meter User Manual for Keithley 2636A* (SOLIS Project, v1.0). Adapt the provided Python control framework to your specific instrumentation following the synchronisation principles outlined in Section 4.

12 Appendix A: Equipment Specifications

12.1 Waveform Generator Requirements

Minimum specifications:

- Dual-channel output
- Frequency range: DC to 1 MHz (sufficient for ms-scale pulses)
- Output voltage: 0–5 V (for LED driver triggering and device biasing)
- Pulse generation capability with adjustable width and period
- Trigger output (TTL-compatible) for synchronizing external instruments
- VISA/SCPI command interface (USB, GPIB, or Ethernet)

Recommended: Multicomp Pro MP751062

- 2 channels, 60 MHz bandwidth
- Arbitrary waveform generation
- External trigger input/output
- USB and LAN connectivity
- Cost: ∼€250

12.2 Digital Multimeter Requirements

Minimum specifications:

- Current measurement range: nA to mA (device-dependent)
- 5.5–6.5 digit resolution
- External trigger input capability
- Measurement speed: $<$ 10 ms per reading (at reduced NPLC)
- VISA/SCPI programmable interface

Recommended: Keysight 34460A

- 6.5-digit Truevolt DMM
- 1 nA to 10 A range
- External trigger support
- NPLC: 0.02–100
- USB, GPIB, LAN interfaces
- Cost: ∼€1,300

Alternative: Single-channel Source meter (e.g., Keithley 2400, 2450) can replace DMM, providing both voltage sourcing and current measurement with better integration.

12.3 LED and Driver Specifications

Fiber-coupled LED requirements:

- Wavelengths: 365–1500 nm (select based on device absorption; subgap defects can also be probed by low energy LEDs)
- Optical power: 1–50 mW (fiber-coupled)
- SMA or FC/PC fiber connector
- Spectral width: 10–50 nm (typical for LEDs)

Recommended wavelengths for thin film synapses:

- 430 nm (blue): CdTe, kesterite, Sb_2S_3 absorption
- 530 nm (green): Broader absorption range
- 625 nm (red): Near bandgap excitation for wider-gap materials
- 850 nm and above (IR): Sub-bandgap excitation, defect-mediated absorption

LED driver requirements:

- External trigger input (TTL, 3.3–5 V)
- Trigger-to-output delay: $<$ 1 µs
- Constant current drive mode
- Current range: 100–1000 mA (LED-dependent)

Recommended: Thorlabs LEDD1B T-Cube

- External trigger input (BNC)
- 1200 mA maximum current
- Modulation bandwidth: DC to 500 kHz
- Cost: ∼€350

12.4 Optical Components

Optical fiber:

- Multimode fiber, 200–600 µm core diameter
- SMA-SMA or FC/PC-FC/PC connectors
- Length: 1–2 m (sufficient for most setups)
- Cost: ∼€50–100

Collimator/focusing optics:

- SMA-threaded collimation package
- Focal length: 11–25 mm (adjustable spot size)
- Optical mount for positioning

- Cost: ~€100–150

Optical power meter:

- Si photodiode detector (350–1100 nm)
- Power range: 1 nW to 100 mW
- Calibration certificate (traceable)
- Cost: ~€500–1,500

13 Appendix B: Timing Diagram Examples

13.1 Configuration A: Keithley 2636A

```
Time axis (ms):
|-----|-----|-----|-----|-----|-----|-----|-----|
0    50   100  150  200  250  300  350  400

Channel B (LED trigger):
||_____________________________________|  (50 ms pulse)

LED output:
||_____________________________________|  (50 ms illumination)

Wait periods:
      |--t_delay--|--t_settle--|
      (50 ms)     (10 ms)

Channel A (read voltage):
                  ||______________|  (V_read ON, measure I)

Current measurement:
                        ||                     (NPLC=1, ~17 ms)

Period: 200 ms
```

13.2 Configuration B: WFG + DMM

```
Time axis (ms):
|-----|-----|-----|-----|-----|-----|-----|-----|
0    50   100  150  200  250  300  350  400

WFG Ch1 (LED trigger):
||_____________________________________|  (50 ms TTL pulse)

LED output:
||_____________________________________|  (50 ms illumination)

WFG Ch2 (V_read):
|__|  (constant bias)

DMM trigger signal:
            ||______________________________  (trigger at t=100 ms)

DMM measurement:
```

```
                    ||______________|  (acquire after t_delay+t_settle)

Period: 200 ms
```

Note: Trigger delays must be calibrated for your specific instruments. Use oscilloscope to verify timing if discrepancies occur.

14 Appendix C: Sample Data Analysis

14.1 Conductance Calculation

Raw data from each pulse:

$$I_n : \text{measured current after pulse } n \text{ [A]} \tag{14}$$

$$V_{\text{read}} : \text{applied read voltage [V]} \tag{15}$$

$$G_n = \frac{I_n}{V_{\text{read}}} \text{ [S]} \tag{16}$$

Units:

- Siemens (S) $= \Omega^{-1}$
- Typical range: nS to µS for thin film devices
- Conversion: 1 nS $= 10^{-9}$ S, 1 µS $= 10^{-6}$ S

14.2 Plasticity Metrics Example

LTP measurement data (example):

- Initial conductance: $G_0 = 50$ nS
- Final conductance (after 100 pulses): $G_{100} = 85$ nS

Calculated metrics:

$$\Delta G = 85 - 50 = 35 \text{ nS} \tag{17}$$

$$\Delta G_{\%} = \frac{85 - 50}{50} \times 100\% = 70\% \tag{18}$$

$$\text{Dynamic range} = \frac{G_{\max}}{G_{\min}} = \frac{85}{50} = 1.7 \text{ (or 70\% increase)} \tag{19}$$

14.3 SRDP Analysis Example

Measured data:

Frequency [Hz]	G_0 [nS]	G_f [nS]	ΔG [nS]
1	50	52	+2
2.5	50	55	+5
5	50	62	+12
10	50	73	+23
25	50	82	+32
50	50	87	+37
100	50	89	+39

Table 4: Example SRDP measurement (100 pulses per frequency)

Interpretation: ΔG increases logarithmically with frequency, saturating above 50 Hz. Critical frequency for substantial potentiation: $f_c \approx$ 5–10 Hz.

14.4 STDP Analysis Example

Expected fit parameters:

- Potentiation amplitude: $A_+ = 30$–40 nS
- Depression amplitude: $A_- = 15$–25 nS
- Time constants: $\tau_+ = \tau_- = 15$–25 ms

Asymmetry index:

$$\mathrm{AI} = \frac{A_+}{A_-} \tag{20}$$

Typical range: AI = 1.5–2.5 (potentiation stronger than depression).

15 Appendix D: Quick Reference Tables

15.1 Typical Protocol Parameters

Protocol	$t_{\mathbf{pulse}}$ [ms]	Period [ms]	$N_{\mathbf{pulses}}$	P_d [mW/cm^2]
LTP	50–500	200–1000	50–200	1–10
LTD (dark)	—	—	—	0 (measure decay)
PPF	10–50	20–100	2 (pair)	5–20
SRDP	10–50	$1/f$	30–100 per f	5–10
STDP	10–20	200–500	30–100 pairs	5–15
JV hysteresis	—	—	—	0 or 1–10

Table 5: Recommended starting parameters for each protocol

15.2 Read Voltage Selection

Device Resistance	$V_{\mathbf{read}}$ [V]	Expected I range
< 1 kΩ	0.05–0.1	50–100 µA
1–100 kΩ	0.1–0.2	1–100 µA
> 100 kΩ	0.2–0.5	10–1000 nA

Table 6: Read voltage selection guidelines (verify linear regime first)

Note: Always verify that V_{read} is in the linear (ohmic) regime of the device IV curve.

15.3 Instrument Settings Summary

Keithley 2636A:

- NPLC: 0.1–1
- Autorange: OFF (set fixed range based on expected current)
- Compliance: $1.2 \times I_{\text{max}}$ (expected maximum current)
- 4-wire sensing: ON (for $R < 100\ \Omega$)

DMM (e.g., Keysight 34460A):

- Function: DC current measurement
- Range: Auto or fixed (nA to mA, device-dependent)
- NPLC: 0.1–1 (fast mode)
- Trigger: External, edge-triggered
- Trigger delay: $t_{\text{delay}} + t_{\text{settle}}$

Waveform generator:

- Ch1: Pulse function, amplitude 3.3–5 V (TTL), width t_{pulse}, period T
- Ch2: DC function, amplitude V_{read}
- Trigger mode: Continuous or single (protocol-dependent)

16 Appendix E: Material-Specific Considerations

16.1 Common Thin Film PV Materials

CdTe:

- Bandgap: 1.45 eV ($\lambda < 850$ nm)
- Recommended LED: 430–625 nm
- Known metastability: Light soaking improves fill factor (Cu migration)
- Expected synaptic behavior: Moderate LTP, strong persistence

CIGS/Kesterite (CZTS):

- Bandgap: 1.0–1.5 eV (tunable with Ga or composition)
- Recommended LED: 530–850 nm
- Known metastability: V_{OC} increase under light soaking (defect reordering)
- Expected synaptic behavior: Strong LTP/LTD, good dynamic range

Sb_2S_3/Sb_2Se_3:

- Bandgap: 1.1–1.7 eV (S vs. Se)
- Recommended LED: 430–730 nm
- Known metastability: Interface defects, persistent photoconductivity
- Expected synaptic behavior: Fast response, wavelength-selective

Perovskite ($CH_3NH_3PbI_3$):

- Bandgap: 1.55 eV
- Recommended LED: 530–730 nm
- Known metastability: Ion migration, strong hysteresis
- Expected synaptic behavior: Very strong memristive behavior, but stability concerns
- *Caution:* Measure in inert atmosphere or encapsulated devices

16.2 Wavelength-Dependent Response

For materials with strong absorption edge, synaptic response varies with wavelength:

Above bandgap ($h\nu > E_g$):

- Strong absorption, high carrier generation
- Fast conductance increase (strong LTP)
- May saturate quickly

Near bandgap ($h\nu \approx E_g$):

- Moderate absorption
- Balanced LTP/LTD dynamics
- Optimal for SRDP/STDP characterisation

Below bandgap ($h\nu < E_g$):

- Defect-mediated absorption
- Slow, persistent conductance change
- Long time constants (suitable for memory applications)

Recommendation: Characterise with 2–3 wavelengths spanning above/near/below bandgap.

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Contributors: SOLIS Consortium (UPC, UniLiv, TalTech, UniVerona, MASCIR, UWC, NIP, Ritsumeikan)

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Contact: For questions, contributions, or reporting errors in this guide, contact the SOLIS coordination team:
Dr. Zacharie Jehl Li-Kao, UPC Barcelona
Email: zacharie.jehl@upc.edu

Companion Software: The SOLIS characterisation software (Python-based, open-source) is available at:
`https://github.com/SOLIS-project/Keithley-2636A-Parameter-analyser`

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