ArC ONE

Memristor Characterisation Platform

User Manual

rev. 1.3.3

Contents

1. Introduction

ArC Instruments® delivers high performance testing platforms for characterizing 'en masse' novel technologies in a fast and automated fashion.

ArC ONE® is specifically designed for working with emerging 2-terminal nanoelectronic memory devices. The instrument is controlled through a simple yet powerful user interface that allows for ArC ONE® capabilities to be broadly accessible, from research students to competent test engineers.

ArC ONE® can effortlessly be integrated into any R&D setting to accelerate discovery. It can be used with any prober for accessing from single up to 1024 devices directly on wafer or even be used as a stand-alone portable testing capability to enable advanced in-situ physicochemical characterisation techniques.

And while this instrument provides unrivalled versatility in testing, it does so without compromising on performance; delivering ns pulsing and other bespoke state-of-art capabilities that are essential for characterising advanced memory devices.

This guide covers the installation of this apparatus and details its capabilities.

2. Getting Started

2.1. Out of the box

The ArC ONE® system consists of a hardware instrumentation board (ArC ONE®) and a dedicated software graphical user interface – GUI (ArC ONE Control®)
The hardware and adjacent components straight out of the box are illustrated below

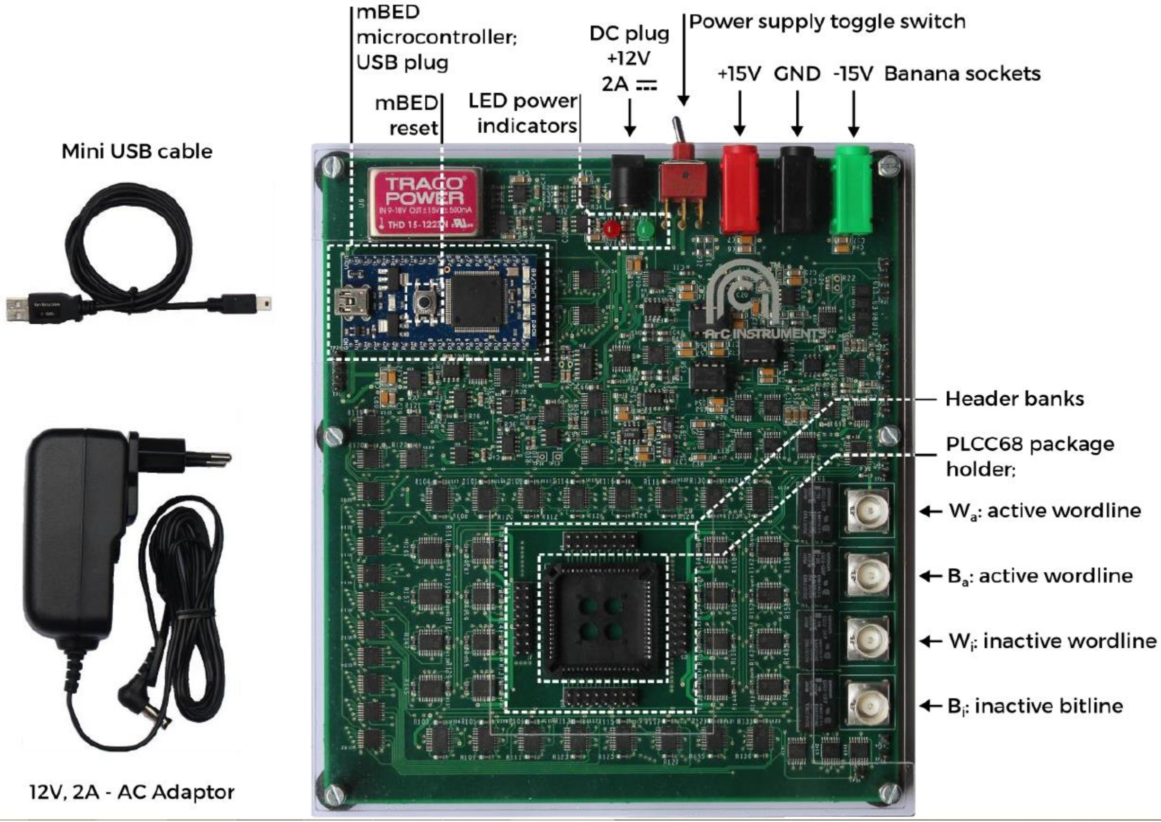


Figure 1: Out of the box: ArC ONE® hardware instrumentation board. Mini USB cable. AC adaptor.

To power up the board, either plug in the provided AC power adaptor in the DC plug, or connect a desktop power supply to the banana sockets. Toggle the power supply switch towards the required power supply input. The red and green LEDs should turn on, indicating the board is powered. For best results, utilise a battery supply.

The PLCC socket holds packaged samples. Its pin map is illustrated below in Figure 2.

In the case where devices need to be accessed away from the board, (eg via a probe card to solid-state devices on wafer), the surrounding headers provide access to individual word- and bitline addresses.

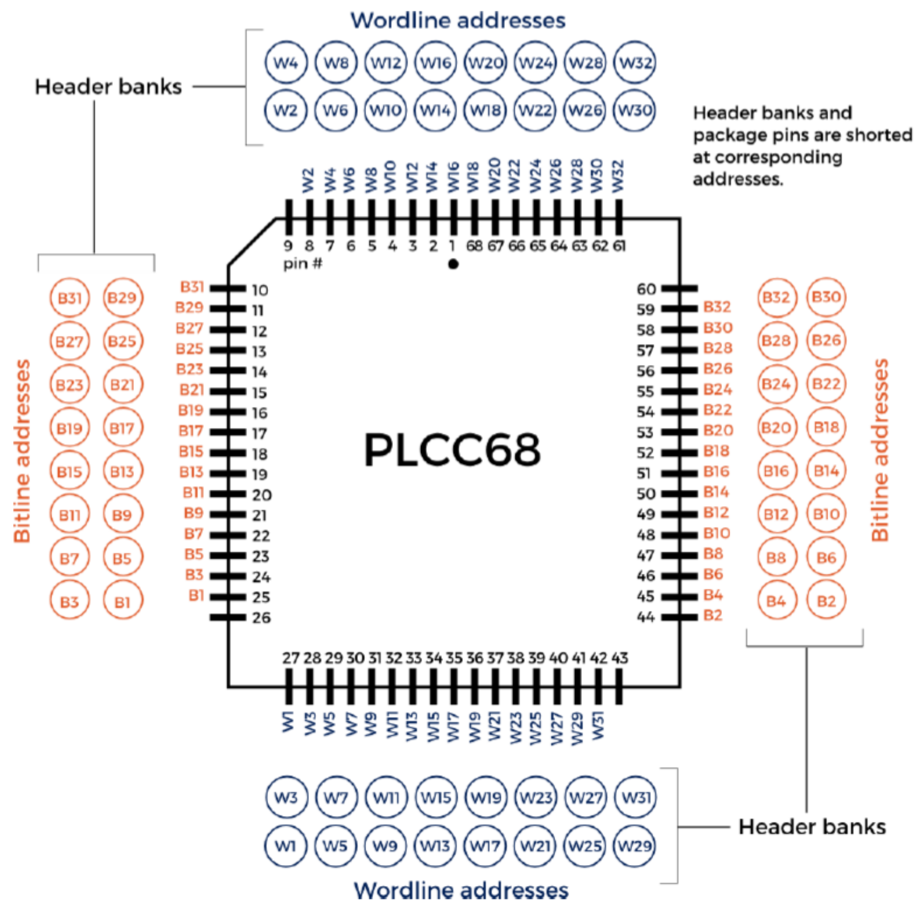


Figure 2: PLCC68 and surrounding headers pin map

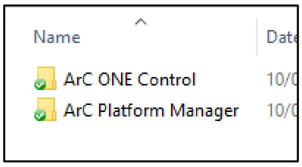
2.2. Software Installation and Update

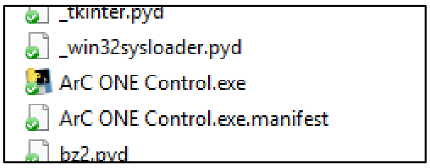
To install the ArC ONE® Control GUI, follow the steps below: (for Windows 7 and 8)

1. Download the source files from:

   http://arc-instruments.com/files/full/ArC_ONE_Control_full.zip

2. Unzip the files to a folder of your choice. The directory should look like below.



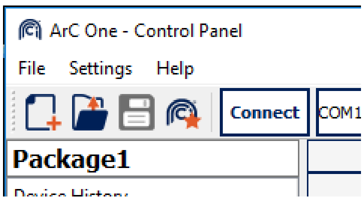


3. Install mBED drivers:

Go to: developer.mbed.org/handbook/Windows-serial-configuration
Follow steps 1 and 2 to install the drivers.

4. You're good to go. Double click on ArC ONE Control.exe in the ArC ONE Control folder to start the interface. Connect your PC to the board via the USB cable and plug in the provided DC adaptor. If you notice any anomalies, reset the mBED.

To update the ArC ONE® Control GUI suite, first start the interface, make sure the ArC ONE® board is connected via USB and look for the Platform Manager launch button on the top left corner of the GUI. An internet connection is required for this feature.



If the button is active, then an update is available. Click the button to start the automatic updater. You can manually check for updates at Settings/Check for updates.

If you encounter any problems, please contact us at office@arc-instruments.co.uk

3. Using the ArC ONE® Control GUI

The ArC ONE® Control GUI is distributed under the General Public License (GNU) Version 3. It is therefore an open-source copy, allowing any user to modify and re-utilise its contents, as long as the original creator is mentioned. Keep a copy of the initial source file to ensure the operation of the ArC® platform.

We are not responsible for any damage to the platform, or computer system utilised by this code. For more information, please consult:

https://www.gnu.org/licenses/gpl-3.0.en.html

3.1. At a Glance

The ArC GUI allows easy control of the ArC ONE® platform. It is divided into a number of functional panels:

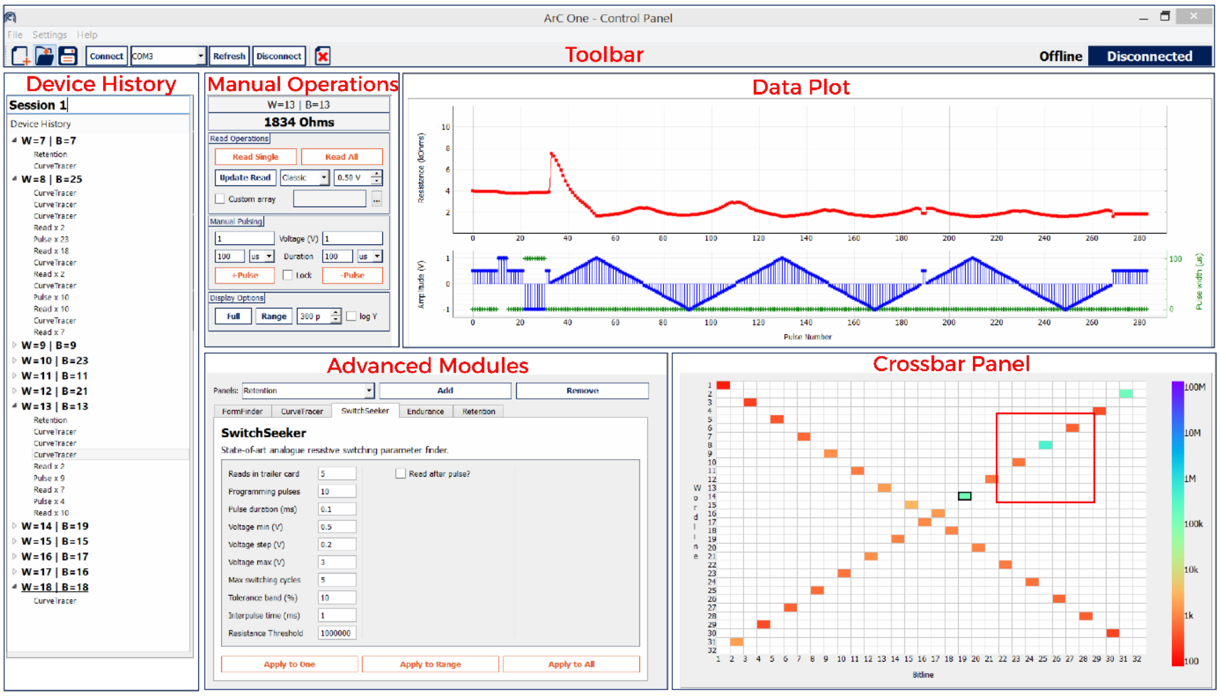


Figure 3: At a glance – functional panels of the ArC ONE® GUI

Toolbar: contains buttons for saving data, creating, opening and clearing a session, ArC ONE® connection management as well as a GUI session mode indicator (refer to Section 3.3) and an ArC ONE® connection indicator, on the right hand side. File menu contains Save, Open, Clear and Exit options. Settings menu allows the user to modify hardware settings and choose a new working directory on the fly. Help menu shows the documentation (this file), and ArC Instruments Ltd. contact information.

Manual Operations panel: Contains buttons for reading a single selected cell or the full array. The Custom Array checkbox restricts the crossbar active devices to any combination of devices in a 32x32 array, based on a text file. The read type can be changed via the drop down menu. The reading voltage can also be set via the input text field. Clicking 'Update' updates the reading method on the ArC ONE® board. Manual pulsing of 0 to ±12V and down to 90ns can be applied on the selected device by pressing +Pulse (positive pulse) or -Pulse (negative pulse). Separate input fields allow for independent setting of positive and negative pulsing polarities.

Crossbar Panel: Direct selection of individual devices is performed by left clicking the required position. The selected crosspoint is highlighted by a thick black outline and represents the current device under test (DUT) for any further operation. The resistive state of each device is represented by the colour of the cell, and the colour coding is illustrated at the right of the crossbar. Hovering over a cross-point reveals the absolute resistance value of the last read operation. Additionally, left clicking and dragging allows selection of a square region of devices in a crossbar if local testing is required.

Data Plot panel: Top plot shows the resistive state evolution of a device. Bottom plot shows the pulse amplitude and pulse duration per pulse number in chronological order. During the application of an automated pulsing script, the plot is updated live with incoming measurement data.

Device History panel: Contains the pulsing history for each device in the crossbar, if any is available. History entries can be accessed to display additional measurement results.

Pulsing Modules panel: The drop-down menu contains a number of custom pulsing scripts, and selecting one displays its corresponding options which the user can then set. Panels include custom device operation scripts such as FormFinder, SwitchSeeker, standard IV measurement protocols such as CurveTracer, and memristor specific characterisation pulsing scripts such as Endurance and Retention. The pulsing scripts are described in detail in Section 3.5.

3.2. Starting a New Session

On starting the GUI, the window on the right below will appear which allows setting up a new measurement session. There are 2 main setting categories:

General Settings:

The Session Mode dropdown selects the operating mode of the system and four options:

1. Live: Local - normal operation mode, all outputs are applied to the on-board package holder, and to the surrounding headers (Figure 5)
2. Live: External BNC – in this mode of operation your device under test should be connected to the instrument through the BNC terminals. The board applies stimuli and reads out data exclusively through the BNC terminals (Figure 6). In the Crossbar Panel the target device appears as address [W=1, B=1]. WARNING: Please ensure no package is connected in the PLCC68 holder or through the header bank.
3. Live: BNC to Local – in this operating regime the instrument's biasing circuitry is disabled and all voltage/current biasing to target devices is provided through the BNC terminals (Figure 7). The ArC platform only performs routing, i.e. directs bias voltages/currents from the BNCs to the selected device (in PLCC68 package or via header banks).
4. Offline – mode used to visualize previously acquired measurements through the ArC system. ArC ONE® biasing hardware disabled.

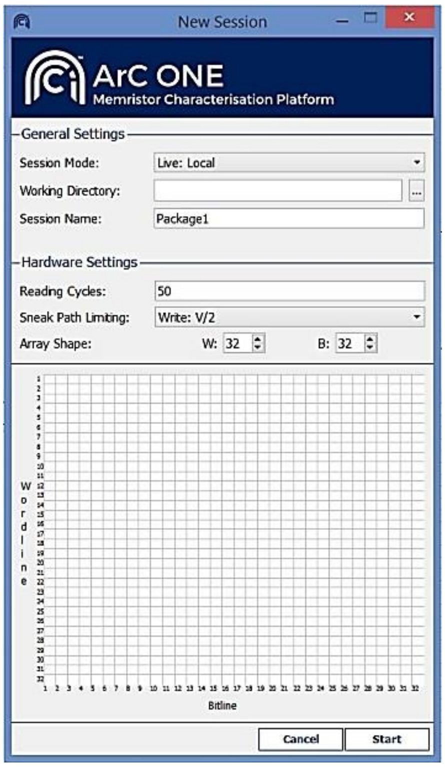


Figure 4: New session panel.

Working Directory entry allows the user to choose the directory in which measurement sessions will be saved. Press the browse button on the right of the entry to navigate. This can be setup later as well.

Session Name entry sets the name of the session.

Hardware Settings:

Reading Cycles: Every test device resistive state READ measurement is by default an average of n recorded data points. This entry sets the value of n. A higher number translates into a slower, but more accurate measurement. n=50 is a reasonable, general purpose choice.

Sneak Path Limiting sets up the sneak path mitigation technique employed in selectorless crossbar arrays. The user can chose between V/2, V/3.

	Sneak Path Limiting Option	
Biasing Nodes	V/2	V/3
Active wordline	V_{write}	V_{write}
Active bitline	GND	GND
Inactive wordline	$V_{write}/2$	$2*V_{write}/3$
Inactive bitline	$V_{write}/2$	$V_{write}/3$

Array Shape counters set up the size of the array. Any size is selectable between 1 and 32 word- and bitlines.

Press Start to start a new session with the selected settings. Cancel to abort.

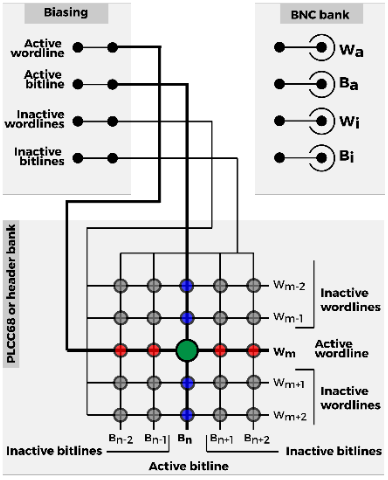


Figure 5: Live: Local session mode board connectivity.

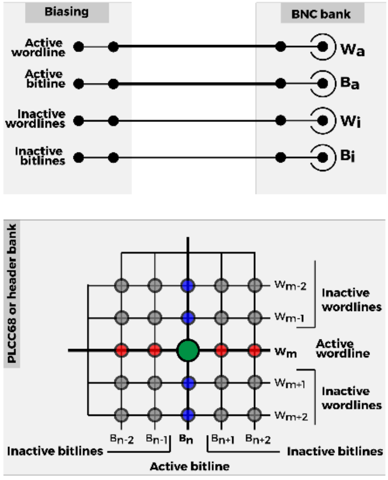


Figure 6: Live: External BNC session mode board connectivity.

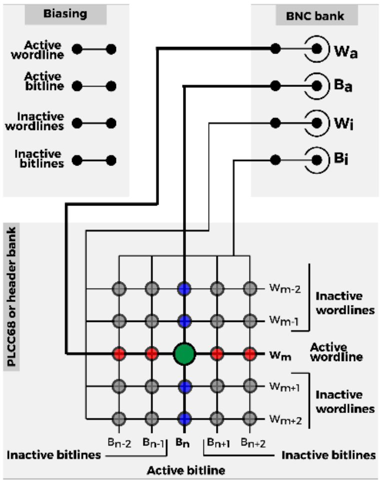


Figure 7: Live: BNC to Local session mode board connectivity.

3.3. Connecting to ArC ONE®

After the new session has been set up, the right hand side of the toolbar should indicate the session mode, and the connection status showing Disconnected as below.

Make sure ArC ONE® is connected to the PC via an USB cable, and the board is powered up. A blue LED on the on-board mBED indicates the board is connected to the PC, and red and green LEDs indicate the board is powered up.

From the toolbar (above), select the corresponding COM port of the ArC ONE® board. If you don't know it, you can find it in Windows by going to:

- Right click **My Computer;**
- Select **Manage;**
- On the left hand side, select **Device Manager;**
- Search for **Ports (COM and LTP)** and expand;
- Look for a device named: **mbed Serial Port (COMX),** and make a note of the COM port number.

Return to the GUI and select the respective COM port from the dropdown list, and click Connect. If the port is not there, click Refresh and wait for up to 10 seconds. The port should now appear.

Once the connection is successful, the connection status will turn green like below:

If any connection problems occur, please refer to Section 5 of this manual.

3.4. Basic Operations

Many basic operations such as reading and writing, as well as data display and device history visualisation are available at a click of a button. As a general rule of thumb, the buttons coloured in orange perform invasive operations on the selected device, or range of devices. Buttons coloured in **dark blue** perform non-invasive operations, such as updating ArC ONE® settings or managing data display options.

Device Selection

Left click the required device on the Crossbar Panel to select it. The device will be highlighted by a black outline. Any following invasive operation will be performed on that device.

Hovering the mouse over a crossbar device shows address and resistance information in the small floating information panel.

The address of the currently selected device appears on top of the Manual Operations panel, along with its corresponding last measured value of resistance.

Left click and drag in order to select a range of devices. A box with a thick red outline will indicate the selected sub-array. Right click anywhere on the Crossbar Panel to toggle the visibility of the box.

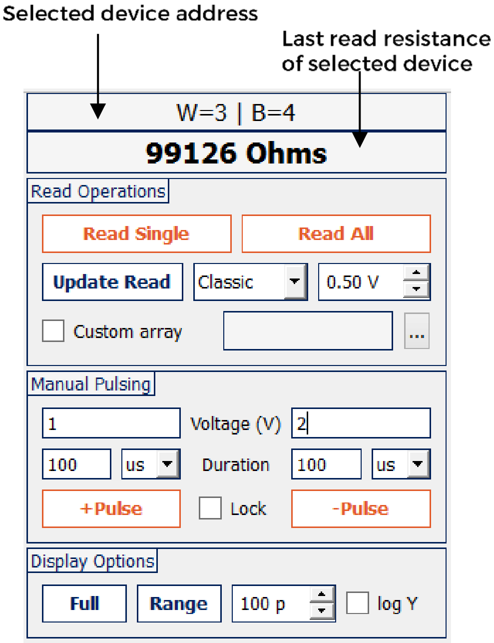


Figure 8: Manual Operations Panel.

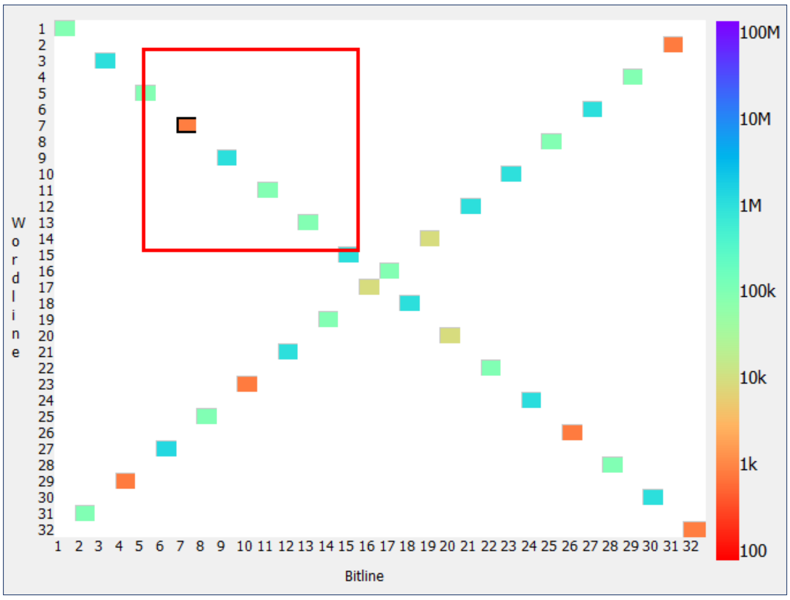


Figure 9: Crossbar Panel showing device range selection.

Custom Arrays

If only a particular set of crosspoints is required for a measurement session, these can be selected on the interface via checking the Custom Array checkbox. A file open dialogue will appear which allows the user to select a text file containing the required addresses, formatted in the following way:

Wordline, Bitline

```
1, 1
2, 31
3, 3
4, 29
5, 5
6, 27
7, 7
8, 25
9, 9
10, 23
11, 11
12, 21
13, 13
14, 19
```

Figure 10: Custom array file format example.

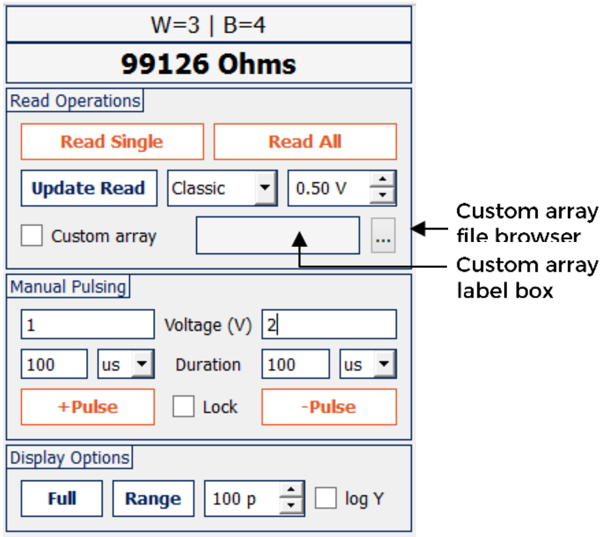


Figure 11: Manual Operations panel – custom array controls.

The same open file dialogue will appear if the browse array file button is pressed.
The set of device addresses are then highlighted in the Crossbar Panel, while the others are hidden. Any device select, or device operation will be constrained to this set.
The devices within the range selected by left clicking and dragging will constitute the target area for any operations carried out via the Apply to Range directive.

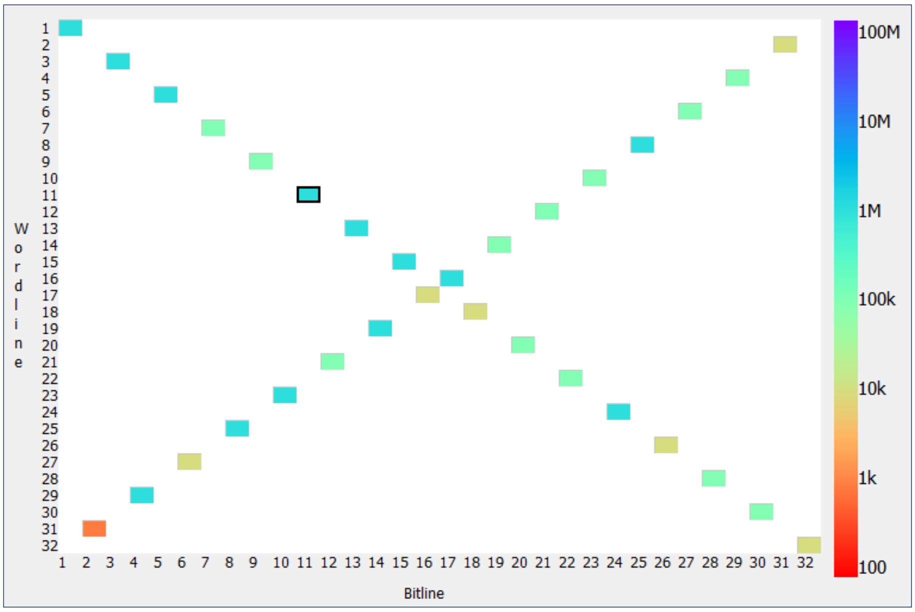


Figure 12: Example of a custom array.

Read Operation

In the Read Operations sub-panel, click Read Single to perform one READ operation on the selected device (highlighted in the Crossbar Panel, and listed on top of the Manual Operations panel). The new value of resistance is updated there.
The Data Plot panel will be updated with the new measurement.

Click Read All to read all devices in the crossbar.

Update Read updates the reading method on the ArC board. Select the reading method between:
1. Classic: reads at 0.5V, suitable for linear resistors, fast;
2. TIA: reads at a programmable voltage;
3. TIA4P: RECOMMENDED - Kelvin sensing at a programmable voltage;

Select the reading voltage by left-clicking the up and down arrows in the reading voltage counter, or introducing a float number by hand.
Remember to click Update Read every time the reading method, or reading voltage is changed.

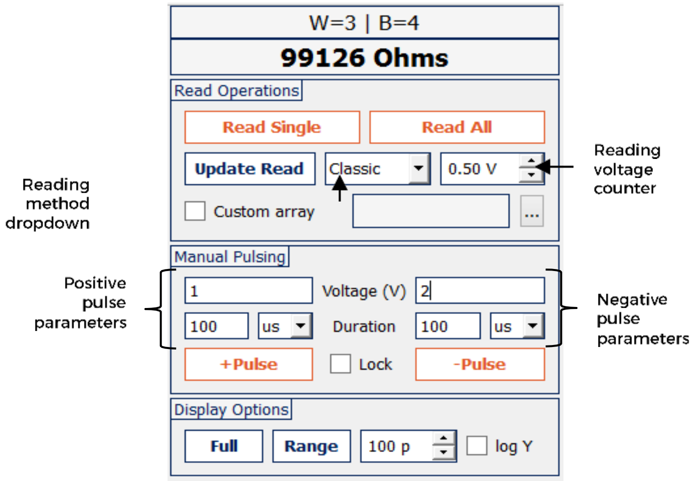


Figure 13: Manual Operations panel.

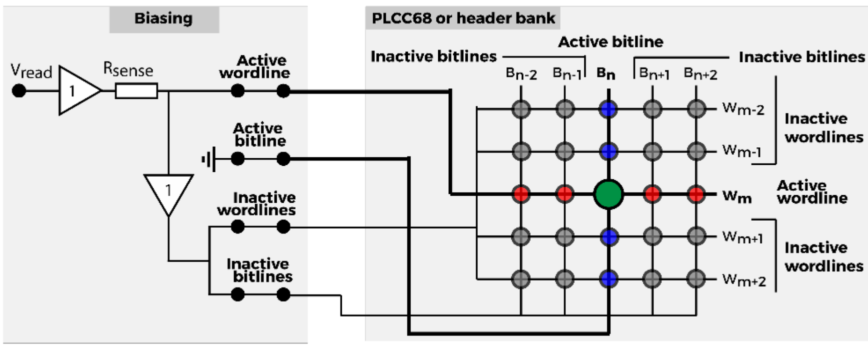


Figure 14: ReadClassic schematic illustration.

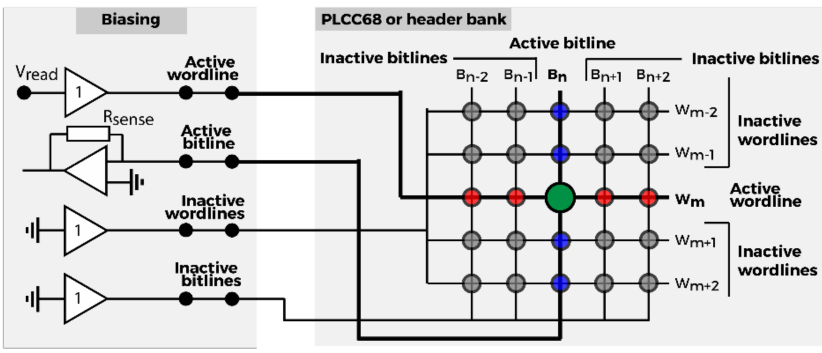


Figure 14: TIA-based read schematic illustration.

Manual Write Pulsing

In the Manual Pulsing sub-panel, single WRITE pulses can be applied on a selected device.

Click the +Pulse to immediately apply a positive voltage pulse, and –Pulse to apply a negative pulse. The parameters of the pulse, such as amplitude and duration, can be changed via the entry fields above the corresponding buttons.

A READ operation is automatically performed after each manual pulse. The new measurement is added in the Data Plot panel, along with the applied manual pulse.

Checking the Lock checkbox disables the negative pulse parameter entry fields. Clicking –Pulse will then apply a negative pulse with the parameters of the positive pulse entry fields.
For example: positive pulse parameters are 1V 100ms, negative pulse parameters are 2V 1ms. Clicking +Pulse will apply 1V 100ms, -Pulse will apply 2V 1ms. After checking the Lock checkbox, clicking +Pulse will apply 1V 100ms, and –Pulse will apply -1V 100ms.

Data Display

In the Display Options sub-panel, the user can modify the plot options in the Data Plot panel.

Press Full to display all recorded data points for the selected device.
Press Range to display the last X number of points, where X is set in the adjacent counter.
Tick the log Y checkbox to set logarithmic Y axis in the top subplot of the Data Plot panel.

Understanding the Data Plot panel.

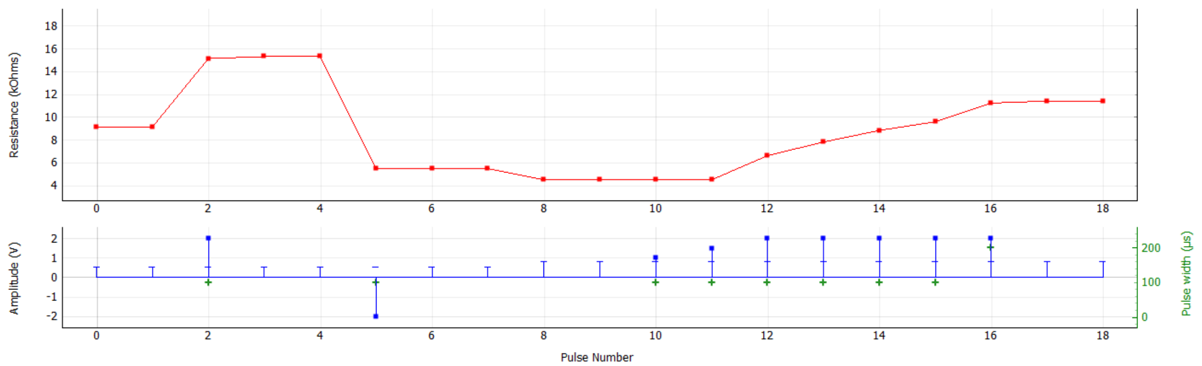


Figure 15: Example Data Plot

Top subplot shows read value of resistance at each pulse number.
Bottom subplot shows:

- Blue horizontal line marker shows the voltage at which the respective resistance data point was measured at.
- Blue square marker shows a WRITE voltage pulse amplitude
- Green '+' marker shows the pulse width of a WRITE voltage pulse, shown on the right hand side Y axis.

A WRITE pulse followed by a READ pulse are displayed in the same pulse number on the x-axis: a blue square marker showing the WRITE pulse amplitude, and a blue horizontal line showing the read voltage of the consecutive READ pulse. The resulting value of resistance measured during the

Figure 16: Example of a data plot showing evolution of resistance during an arbitrary manual pulsing session.

For example, in Figure 16 at pulse #1, the resistance is read at 0.5V as ~9kΩ. Next, a 2V, 100μs voltage pulse is applied shown at pulse#2. The resistance is then automatically read as 15kΩ, also at 0.5V, indicated by the blue horizontal line marker at the same pulse #2. Therefore, a 2V, 100μs voltage pulse has changed the resistance of the device as read at 0.5V, from 9kΩ to 15kΩ.

Right click on the Data Plot panel for extra display options such as setting custom x and y-axis range, or exporting the figure image files.

Device History

All invasive device operations are logged in the Device History panel.
Device addresses are added from top to bottom in a chronological order following any operation.
The last device address where an operation was performed is underlined.
Selecting a device address from the Device History panel will also select and display its pulsing history in the Data Plot panel.

Single device operations are listed below its corresponding address from top to bottom in a chronological order.
These become visible by clicking the dropdown marker.

READ operations are tagged with Read x N, where N is the number of read pulses applied in sequence.
WRITE operations are tagged with Pulse x N, where N is the number of manual WRITE pulses applied in sequence.

Advanced pulsing algorithms are tagged with their corresponding name.
Double clicking some advanced pulsing algorithm entries displays further measurement results.
For example, following a CurveTracer measurement, double clicking the 'CurveTracer' history entry will display the resulting IV curve. See Section 3.5 for more information.

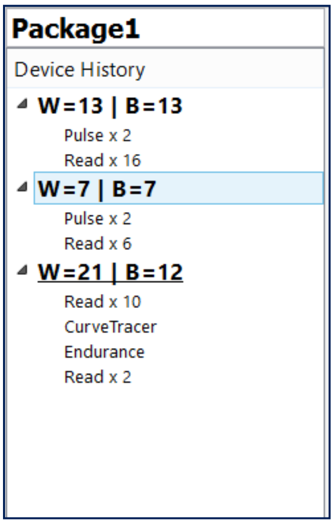


Figure 17: Device history panel example.

Saving Data

All raw data is saved in standard .csv files by clicking the save button in the toolbar. Every READ or WRITE operation is represented as a line entry in this file, following the format below:

```
Wordline, Bitline, Resistance, Amplitude, PulseWidth, Tag, ReadTag, ReadVoltage
```

Wordline, Bitline: target device address.
Resistance: Last read resistance of the target device.
Amplitude: WRITE pulse amplitude for WRITE operation, READ pulse amplitude for READ operation.
CAUTION: In the case of a WRITE operation, the READ pulse amplitude is not stored!
PulseWidth: Pulse duration. CAUTION: Marked as '0' for READ operations!
Tag: Descriptive tag providing extra information regarding the respective data point.
ReadTag: RX: X represents the read type employed for the READ operation during the respective point measurement.
ReadVoltage: represents the reading voltage employed for the READ operation during the respective measurement point.

Tag	Description	Observation
F R*X* V=*V_{read}*	A read operation recorded following Read All. *X* represents the read type employed: 0. Classic 1. TIA 2. TIA4P *V_{read}* represents the reading voltage (in V).	Data point is not recorded in the Device History panel. V_{read} is also recorded in the Amplitude column. PulseWidth is recorded as 0.
S R*X* V=*V_{read}*	A read operation recorded following Read Single. All other indicators identical to above.	Data point is displayed in Device History panel. PulseWidth is recorded as 0.
P	Pulse applied through the +Pulse or –Pulse directives in the Manual Operations panel of the interface.	The 'Resistance' field contains the resistance of the target device as read immediately after the application of the pulse. Compare to the value read before the pulse to quantify the change in resistance elicited by this pulse.
CT_s	Start point of a CurveTracer measurement.	Resistance represents the resistance of the device read at V_{read}=Amplitude. PulseWidth is recorded as 0.
CT_i_*x*	Intermediate data points during a CurveTracer measurement. *x* represents the cycle number.	Same as above.
CT_e	End point of a CurveTracer measurement.	Same as above
FF_s	Start of a FormFinder measurement.	The 'Resistance' field contains the resistance of the target device as read immediately after the application of the pulse. Compare to the value read before the pulse to quantify the change in resistance elicited by this pulse.
FF_i	Intermediate point of a FormFinder measurement	Same as above
FF_e	End point of a FormFinder measurement.	Same as above
SS_s	Start of a SwitchSeeker measurement	The 'Resistance' field contains the resistance of the target device as read immediately after the application of the pulse. Compare to the value read before the pulse to quantify the change in resistance elicited by this pulse.
SS_i	Intermediate point of a SwitchSeeker measurement	Same as above
SS_e	End point of a SwitchSeeker measurement	Same as above
RET_s	Start of a Retention measurement.	READ voltage shown in 'Amplitude' field.

RET_*x*	Intermediate point of a Retention measurement. *x* indicates the time point in seconds of each measurement.	Same as above
RET_e	End of a Retention measurement	Same as above
EN_s	Start of Endurance measurement	WRITE voltage pulse parameters saved in 'Amplitude' and 'PulseWidth' fields. 'Resistance' field contains the resistance of the target device as read immediately after the application of the pulse.
EN_i	Intermadiate point of Endurance measurement	Same as above
EN_e	End point of Endurance measurement	Same as above

Example Measurement

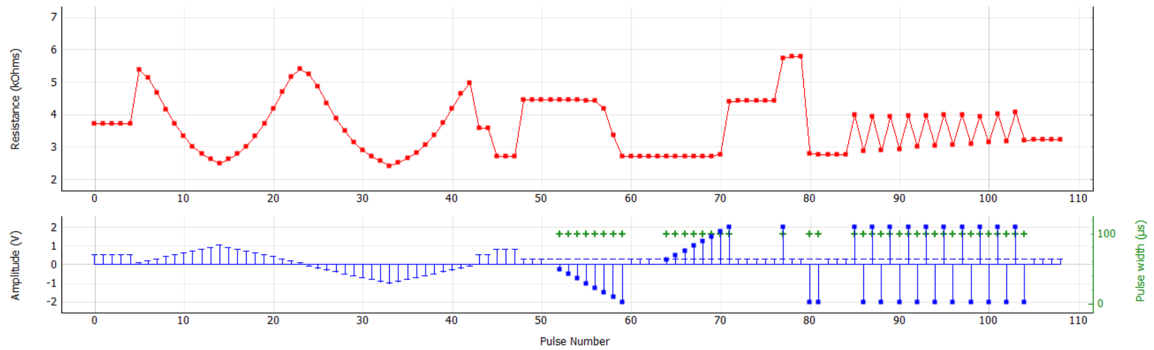


Figure 178: Example measurement raw data display in the Data Plot.

The example plot coincides with the raw data listed below, from one device at address W=15, B=15.

Pulse #	Wordline	Bitline	Resistance	Amplitude (V)	(s)	Tag	ReadTag	Vread
0	15	15	3710.626	0.5	0	S R2 V=0.5	R2	0.5
1	15	15	3709.371	0.5	0	S R2 V=0.5	R2	0.5
2	15	15	3711.8	0.5	0	S R2 V=0.5	R2	0.5
3	15	15	3711.342	0.5	0	S R2 V=0.5	R2	0.5
4	15	15	3712.748	0.5	0	S R2 V=0.5	R2	0.5
5	15	15	5387.196	0.095865	0	CT_s	R2	0.095865
6	15	15	5132.203	0.197452	0	CT_i_1	R2	0.197452
7	15	15	4678.331	0.298781	0	CT_i_1	R2	0.298781
8	15	15	4168.121	0.399095	0	CT_i_1	R2	0.399095
9	15	15	3710.786	0.498812	0	CT_i_1	R2	0.498812
10	15	15	3329.797	0.601575	0	CT_i_1	R2	0.601575
11	15	15	3015.44	0.706225	0	CT_i_1	R2	0.706225
12	15	15	2788.292	0.810664	0	CT_i_1	R2	0.810664
13	15	15	2623.501	0.912557	0	CT_i_1	R2	0.912557
14	15	15	2490.076	1.014837	0	CT_i_1	R2	1.014837

15	15	15	2621.308	0.912573	0	CT_i_1	R2	0.912573
16	15	15	2789.779	0.810455	0	CT_i_1	R2	0.810455
17	15	15	3020.242	0.706225	0	CT_i_1	R2	0.706225
18	15	15	3331.286	0.601511	0	CT_i_1	R2	0.601511
19	15	15	3720.155	0.498795	0	CT_i_1	R2	0.498795
20	15	15	4177.835	0.398998	0	CT_i_1	R2	0.398998
21	15	15	4687.421	0.298636	0	CT_i_1	R2	0.298636
22	15	15	5160.943	0.197452	0	CT_i_1	R2	0.197452
23	15	15	5411.013	0.095865	0	CT_i_1	R2	0.095865
24	15	15	5234.892	-0.09978	0	CT_i_1	R2	-0.09978
25	15	15	4851.898	-0.20206	0	CT_i_1	R2	-0.20206
26	15	15	4356.187	-0.30347	0	CT_i_1	R2	-0.30347
27	15	15	3871.069	-0.40329	0	CT_i_1	R2	-0.40329
28	15	15	3491.388	-0.5044	0	CT_i_1	R2	-0.5044
29	15	15	3146.329	-0.60612	0	CT_i_1	R2	-0.60612
30	15	15	2899.183	-0.70682	0	CT_i_1	R2	-0.70682
31	15	15	2710.133	-0.8068	0	CT_i_1	R2	-0.8068
32	15	15	2563.161	-0.90872	0	CT_i_1	R2	-0.90872
33	15	15	2415.091	-1.01092	0	CT_i_1	R2	-1.01092
34	15	15	2515.301	-0.9085	0	CT_i_1	R2	-0.9085
35	15	15	2652.484	-0.80683	0	CT_i_1	R2	-0.80683
36	15	15	2830.457	-0.70664	0	CT_i_1	R2	-0.70664
37	15	15	3060.042	-0.60627	0	CT_i_1	R2	-0.60627
38	15	15	3369.232	-0.50439	0	CT_i_1	R2	-0.50439
39	15	15	3738.675	-0.40321	0	CT_i_1	R2	-0.40321
40	15	15	4194.151	-0.3035	0	CT_i_1	R2	-0.3035
41	15	15	4640.74	-0.20174	0	CT_i_1	R2	-0.20174
42	15	15	4973.099	-0.09959	0	CT_e	R2	-0.09959
43	15	15	3578.096	0.5	0	S R2 V=0.5	R2	0.5
44	15	15	3580.594	0.5	0	S R2 V=0.5	R2	0.5
45	15	15	2714.075	0.8	0	S R2 V=0.8	R2	0.8
46	15	15	2715.643	0.8	0	S R2 V=0.8	R2	0.8
47	15	15	2715.713	0.8	0	S R2 V=0.8	R2	0.8
48	15	15	4449.561	0.3	0	S R2 V=0.3	R2	0.3
49	15	15	4454.619	0.3	0	S R2 V=0.3	R2	0.3
50	15	15	4454.496	0.3	0	S R2 V=0.3	R2	0.3
51	15	15	4453.649	0	0	FF_s	R2	0.3
52	15	15	4455.347	-0.25	0.0001	FF_i	R2	0.3
53	15	15	4450.094	-0.5	0.0001	FF_i	R2	0.3
54	15	15	4448.665	-0.75	0.0001	FF_i	R2	0.3
55	15	15	4437.407	-1	0.0001	FF_i	R2	0.3
56	15	15	4420.111	-1.25	0.0001	FF_i	R2	0.3
57	15	15	4171.116	-1.5	0.0001	FF_i	R2	0.3
58	15	15	3355.073	-1.75	0.0001	FF_i	R2	0.3
59	15	15	2714.42	-2	0.0001	FF_e	R2	0.3
60	15	15	2717.5	0.3	0	S R2 V=0.3	R2	0.3
61	15	15	2717.707	0.3	0	S R2 V=0.3	R2	0.3
62	15	15	2717.669	0.3	0	S R2 V=0.3	R2	0.3
63	15	15	2717.591	0	0	FF_s	R2	0.3
64	15	15	2719.074	0.25	0.0001	FF_i	R2	0.3
65	15	15	2718.968	0.5	0.0001	FF_i	R2	0.3
66	15	15	2716.181	0.75	0.0001	FF_i	R2	0.3
67	15	15	2715.721	1	0.0001	FF_i	R2	0.3
68	15	15	2713.022	1.25	0.0001	FF_i	R2	0.3
69	15	15	2713.36	1.5	0.0001	FF_i	R2	0.3
70	15	15	2776.728	1.75	0.0001	FF_i	R2	0.3
71	15	15	4390.111	2	0.0001	FF_e	R2	0.3
72	15	15	4414.533	0.3	0	S R2 V=0.3	R2	0.3
73	15	15	4420.807	0.3	0	S R2 V=0.3	R2	0.3
74	15	15	4421.931	0.3	0	S R2 V=0.3	R2	0.3

75	15	15	4438.629	0.3	0	S R2 V=0.3	R2	0.3
76	15	15	4437.45	0.3	0	S R2 V=0.3	R2	0.3
77	15	15	5745	2	1.00E-04	P	R2	0.3
78	15	15	5791.744	0.3	0	S R2 V=0.3	R2	0.3
79	15	15	5794.007	0.3	0	S R2 V=0.3	R2	0.3
80	15	15	2802	-2	1.00E-04	P	R2	0.3
81	15	15	2759	-2	1.00E-04	P	R2	0.3
82	15	15	2763.08	0.3	0	S R2 V=0.3	R2	0.3
83	15	15	2761.165	0.3	0	S R2 V=0.3	R2	0.3
84	15	15	2762.447	0.3	0	S R2 V=0.3	R2	0.3
85	15	15	3999.051	2	0.0001	EN_s	R2	0.3
86	15	15	2861.266	-2	0.0001	EN_i	R2	0.3
87	15	15	3936.899	2	0.0001	EN_i	R2	0.3
88	15	15	2888.566	-2	0.0001	EN_i	R2	0.3
89	15	15	3927.748	2	0.0001	EN_i	R2	0.3
90	15	15	2935.807	-2	0.0001	EN_i	R2	0.3
91	15	15	3960.851	2	0.0001	EN_i	R2	0.3
92	15	15	3010.295	-2	0.0001	EN_i	R2	0.3
93	15	15	3975.576	2	0.0001	EN_i	R2	0.3
94	15	15	3030.883	-2	0.0001	EN_i	R2	0.3
95	15	15	4004.491	2	0.0001	EN_i	R2	0.3
96	15	15	3069.084	-2	0.0001	EN_i	R2	0.3
97	15	15	3993.906	2	0.0001	EN_i	R2	0.3
98	15	15	3098.52	-2	0.0001	EN_i	R2	0.3
99	15	15	3931.544	2	0.0001	EN_i	R2	0.3
100	15	15	3140.177	-2	0.0001	EN_i	R2	0.3
101	15	15	4010.678	2	0.0001	EN_i	R2	0.3
102	15	15	3161.425	-2	0.0001	EN_i	R2	0.3
103	15	15	4076.823	2	0.0001	EN_i	R2	0.3
104	15	15	3209.966	-2	0.0001	EN_e	R2	0.3
105	15	15	3215.763	0.3	0	S R2 V=0.3	R2	0.3
106	15	15	3215.978	0.3	0	S R2 V=0.3	R2	0.3
107	15	15	3216.013	0.3	0	S R2 V=0.3	R2	0.3
108	15	15	3215.842	0.3	0	S R2 V=0.3	R2	0.3

3.5. Advanced Pulsing Modules

Several advanced pulsing scripts are available in the Pulsing Modules panel. These are:

FormFinder: applies a pulsed voltage ramp; stops when the resistance has overshot an absolute, or proportional programmable value. Normally used for electroforming.

CurveTracer: standard, low frequency pulsed IV measurement module.

Endurance: Cycle switch a device between ON and OFF values, for any number of cycles.

Retention: Measure the resistive state of a device periodically for a fixed overall duration.

SwitchSeeker: Assuming a bipolar device, apply voltage pulses of increasing width and amplitude of both polarities in order to extract the pulse parameters which elicits repeatable analogue RS.

All pulsing scripts are available in the Panels dropdown list. Select the desired one and press Add to load it in the panel. To remove a module, select the corresponding tab and press Remove.

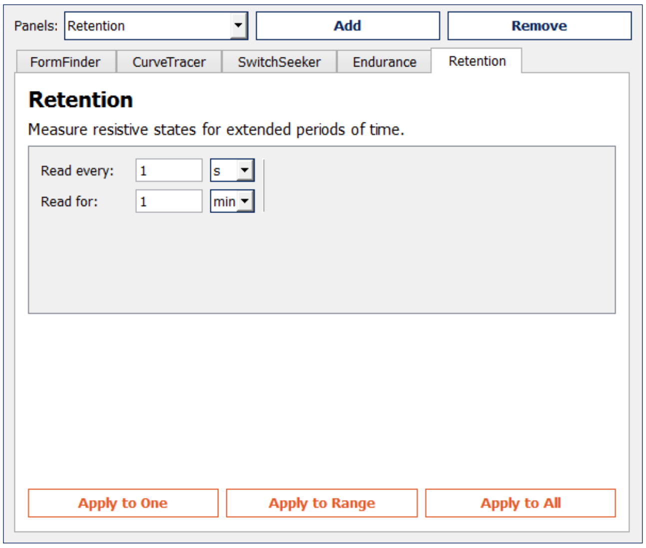


Figure 19: Pulsing panel example.

Apply to One, Apply to Range and Apply to All buttons are standard to all advanced pulsing algorithms provided by ArC.

Apply to One: applies the algorithm to the currently selected device only.
Apply to Range: applies the algorithm to the currently selected range of devices.
Apply to All: applies the algorithm to all available devices in the array.

FormFinder

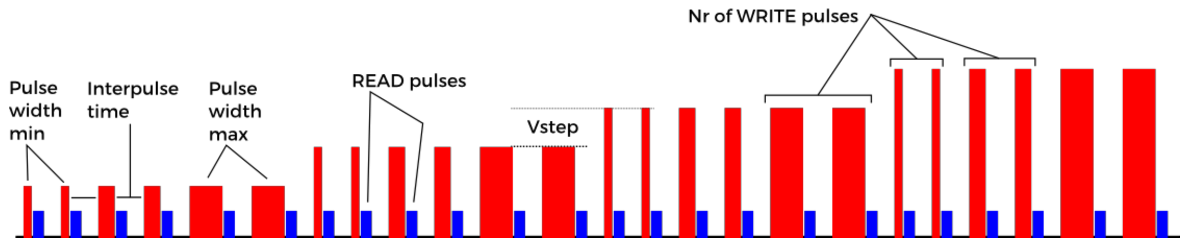


Figure 18: Illustration of FormFinder pulsing algorithm.

FormFinder is a versatile pulsing algorithm which applies a pulsed voltage ramp with an option of two stop conditions. After each WRITE pulse, a READ pulse is applied by default.

The algorithm has several programmable parameters:

Voltage min (V): sets the start voltage of the ramp.

Voltage step (V): sets the step voltage of the ramp.

Voltage max (V): sets the maximum voltage that the ramp can achieve; also acts as a stop condition.

Pulse width min (us): sets the start value of pulse width.

Pulse width step (%): sets the proportional pulse width step value.

Pulse width max (us): sets the maximum pulse width achievable during a pulse batch.

Interpulse time (ms): sets the interpulse timing between two adjacent WRITE pulses.

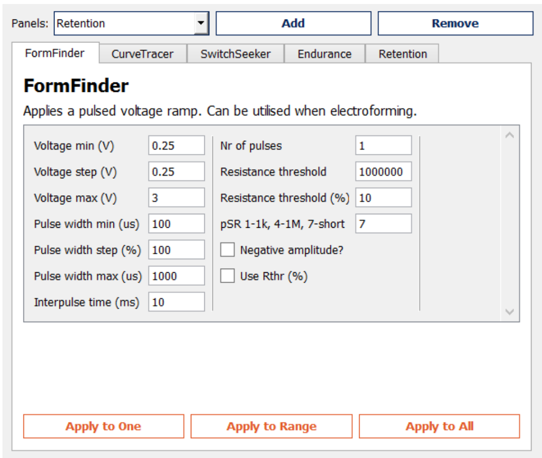


Figure 19: FormFinder options panel.

Nr of pulses: sets the number of identical pulses to be applied in sequence during one pulse batch.

Resistance threshold: halts the ramp when the resistance of the device has undershot this value. This stop condition is implemented by default.

Resistance threshold (%): halts the ramp when the resistance has changed by this % value compared to an initial read value.

pSR 1-1k, 4-1M, 7-short: sets a series limiting resistor: 1 - 1kΩ; 2 - 10kΩ; 3 – 100kΩ; 4 – 1MΩ; 7 – no series resistor (short circuit).

Negative amplitude checkbox: applies the full ramp with negative amplitude pulses.

Use Rthr (%): utilises the proportional (%) stop condition setup in Resistance threshold (%) entry when ticked.

A standard pulsed voltage ramp, with one pulse per step can be achieved by setting Nr of pulses to 1, and making Pulse width min (us) and Pulse width max (us) equal to the desired pulse width value.

CurveTracer

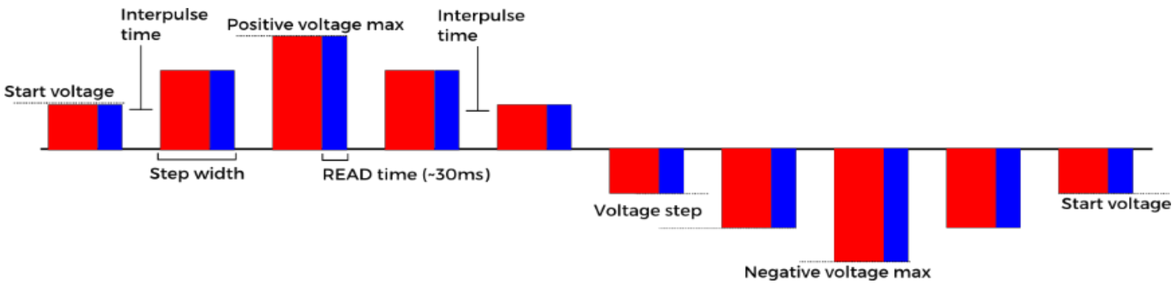


Figure 20: Illustration of CurveTracer pulsing algorithm.

CurveTracer is a standard triangular pulsed IV measurement module, with incorporated current cut-off. During each WRITE pulse, a current measurement is taken towards the end of the pulse.

Positive voltage max (V): sets the maximum voltage during the positive sweep.

Negative voltage max (V): sets the maximum voltage during the negative sweep.

Voltage step (V): sets the step voltage, for both positive and negative sweeps.

Start voltage (V): sets the start voltage value (limited to 50mV).

Step width (ms): sets the width of the pulses, minimum of 1 ms.

Cycles: sets the number of consecutive IV measurements to be taken.

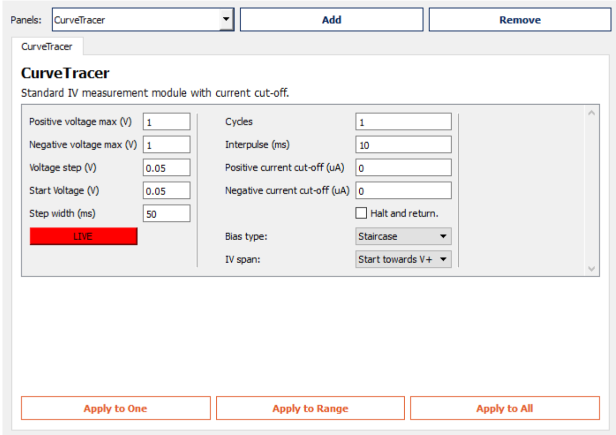


Figure 21: CurveTracer options panel.

Interpulse time (ms): sets the interpulse timing between two adjacent pulses.

Positive current cut-off (uA): Sets the positive current cut-off threshold, variable between 10 and 1000uA. Set to '0' to disable it.

Negative current cut-off (uA): Same as for positive current.

Halt and return checkbox: When checked, the input voltage will cut-off in <30us, then return to 0 in voltage step increments, only after either of the current thresholds have been exceeded. If no current threshold is imposed, the checkbox has no effect.

Bias Type: dropdown menu contains two options: Staircase – where Interpulse time is 0; Pulse – where both terminals of the device are grounded between measurement pulses for the specified interpulse duration ('return to zero' pulsing).

IV span: Dropdown menu containing a selection of IV common sweep run modalities. Decide whether to begin sweeping towards positive or negative voltages, or restrict IV measurement to one voltage polarity only.

Following application of the protocol a 'CurveTracer' entry will appear in the Device History panel. Double click it to visualize the IV measurement as shown in Fig. 22.

Right click on the plots and select Export to save the figure, or corresponding data.

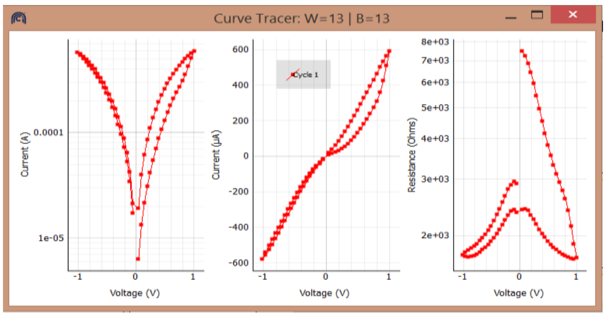


Figure 22: CurveTracer results example.

Live: Pressing this button opens up a panel similar to CurveTracer (Figure 23) offering live display of I-V curves.

GO LIVE! – Starts live measurement.

Apply to One – Applies a normal CurveTracer measurement with programmable nr of cycles via the corresponding entry field.

BufferSize – sets the nr of I-V cycles the panel records in its buffer.

Save Data – saves all the I-V curves recorded in the internal buffer.

The panel has a persistence of 5 I-V curves which are color-coded based on recording time: older I-V curves are coloured in increasingly lighter red.

During a live measurement, all parameters can be changed on-the-fly by entering the corresponding values by hand or scrolling with your mouse while hovering on the entry field.

The I-V figure can be scaled with your mouse by scrolling on its axes, and set to auto-scale automatically by pressing the "A" symbol in the bottom left corner of the figure (this symbol appears when hovering over the unscaled figure).

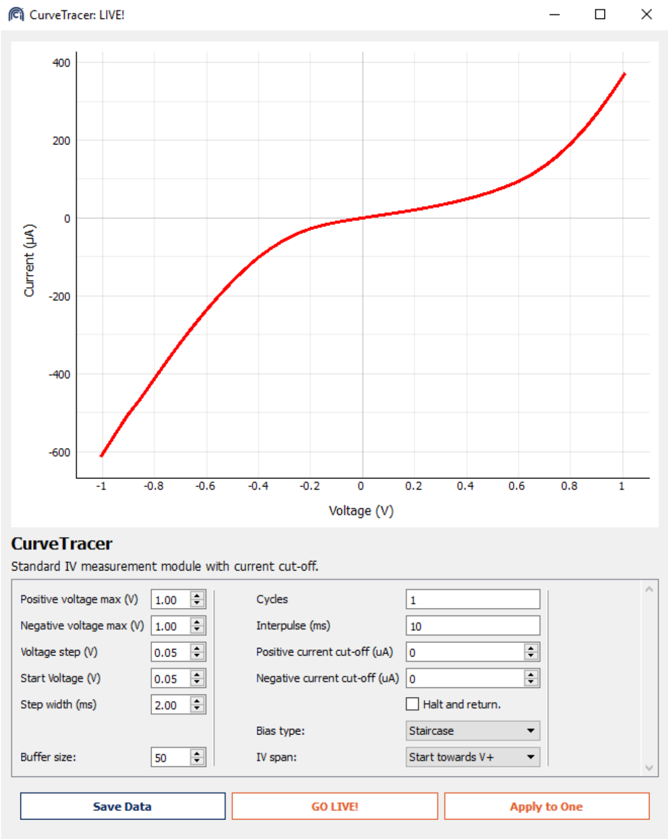


Figure 23: CurveTracer - LIVE

SwitchSeeker

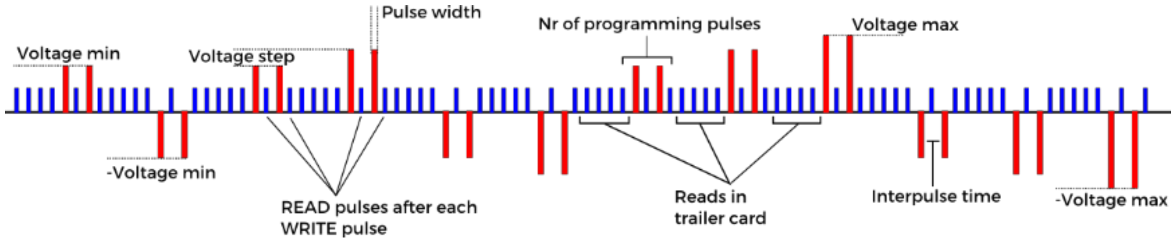


Figure 24: Illustration of SwitchSeeker pulsing algorithm.

SwitchSeeker is a state-of-art analogue resistive switching parameter finder. It automatically extracts the pulse parameters which elicit repeatable analogue resistive switching. It achieves this by applying increasingly invasive alternative polarity pulsed voltage ramps, until the resistance of the device exits a programmable tolerance band. The algorithm consists of two stages: In stage I the system attempts to detect the voltage polarity to which the device is most sensitive by applying a series of alternating polarity pulses with progressively higher voltage. In stage II it applies a series of pulsed voltage ramps in alternating polarities in order to switch the device. An illustration of the pulsing run is shown in Figure 25, and an in depth explanation is provided in ref [3] in Section 4.

Reads in trailer card: sets the number of reading pulses before each pulse batch.

Programming pulses: sets the number of identical pulses in a pulse batch.

Pulse duration: sets the constant pulse width;

Voltage min (V): sets the start voltage of each ramp;

Voltage step (V): sets the voltage step per consecutive batches in the same ramp.

Voltage max (V): sets the voltage step per consecutive batches in the same ramp.

Max switching cycles: sets the number of consecutive cycles the device is switched after the analogue resistive switching parameters have been found.

Tolerance band: sets the tolerance band, as % of the resistance value read before one ramp is applied.

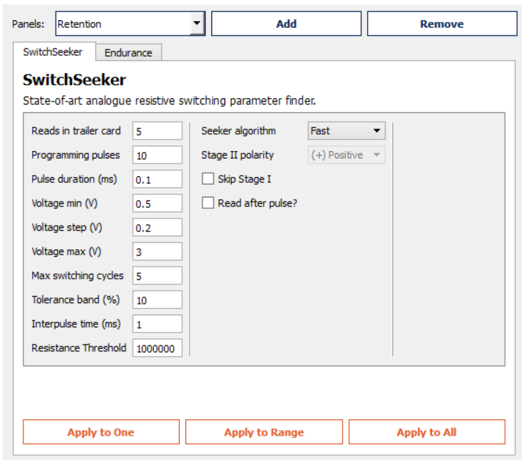


Figure 25: SwitchSeeker options panel.

Interpulse time (ms): sets the interpulse timing.

Resistance threshold (Ohms): If no test device is connected, or it is at extremely high resistive state (well above 10MOhm) measurement noise can be considerable and thus confuse the switchSeeker algorithm. Set a maximum valid resistance threshold to avoid this issue.

Seeker algorithm: decides how to carry out stage I of the algorithm. The options are a 'fast but invasive' method that ramps up the voltage quickly and a 'slow and safe' method that ramps voltage up more gradually. Experiment on a discrete resistor to explore the exact difference.

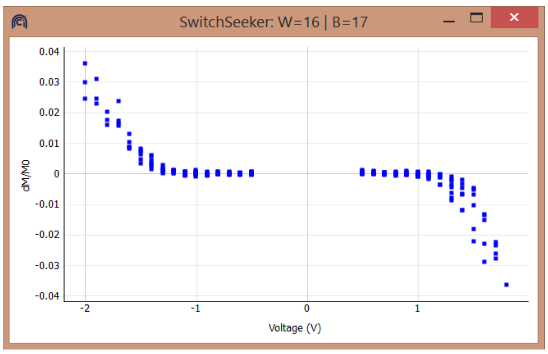


Figure 26: SwitchSeeker resistive switching results.

Skip stage I/stage II polarity: The user may decide to skip stage I of the algorithm, in which case the system will only apply the series of alternating polarity pulsed voltage ramps. The initial polarity can be chosen by the user.

Read after pulse?: checkbox activates reading after each voltage pulse is applied.

A SwitchSeeker entry will appear in the Device History panel. Double click it to visualize the analogue resistive switching results. An example of a SwitchSeeker run result is illustrated in Figure 26.

Right click on the plots and select Export to save the figure, or corresponding data.

Retention

Measure resistive state retention times with this module.

It repeatedly reads the resistive state of a selected, range or full array of devices a specific interval and for a set duration of time.

It utilises the reading method and reading voltage setup in the Manual Operations panel.

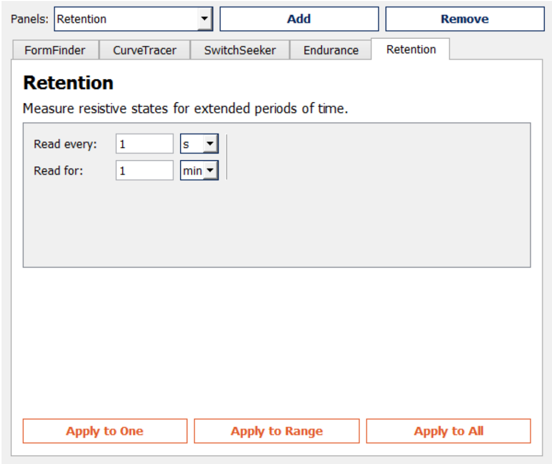


Figure 27: Retention options panel.

Endurance

Measure resistive state switch endurance with this module.

It applies alternating polarity voltage pulse trains to toggle the state of single, range or full array of devices between some ON and OFF values. It is possible to set current cut-off values, independent for both half cycles (SET or RESET) by changing the corresponding parameters.

A read pulse is applied after each programming pulse.

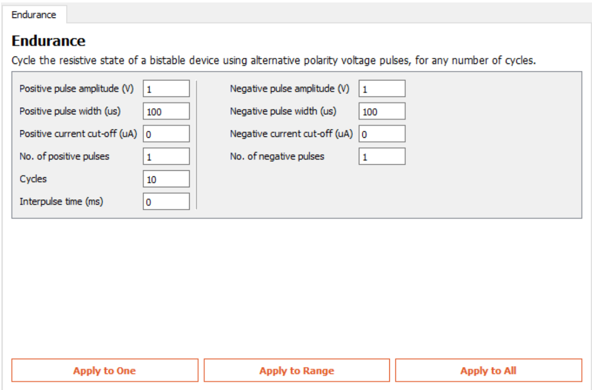


Figure 29: Endurance options panel.

VolatilityRead

Apply a single pulse and then measure the transient response of the device.

The VolatilityRead module begins by applying a single square-wave pulse with parameters specified by the 'Pulse Amplitude' and 'Pulse Width' fields. Subsequently, the instrument starts measuring the resistive state of the device at its maximum sampling rate of 200 ksps. By default, 100 of these 'spot reads' are averaged to yield a single assessment of the resistive state of the DUT, although the user may change that value through the 'Average cycles/point' field. Once B resistive state assessments have been collected (user-defined, 'Read Batch Size' field, max. 1000) the system will interrupt its read-out sequence and transmit data from the microcontroller to the PC, following which the procedure will repeat for as many batches as are required until a stopping condition is met.

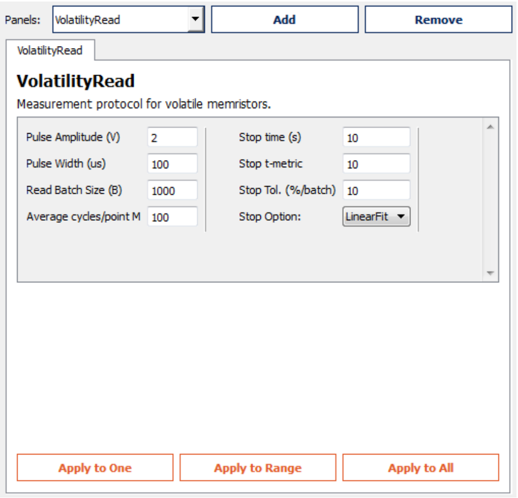


Figure 30: Volatility module interface.

The volatile read module can be configured to use three possible stopping conditions:

a) Fixed time: the system will continue reading batches of data until the 'Stop time' is reached. Note: Once a data batch has started it will finish even if it ends after the prescribed stop time.
b) Linear fit: The system will fit the resistive state of each batch with an affine relation. If the absolute slope measured in % change of resistive state per batch drops below the value specified by the 'Stop Tol.' field, the system considers the device to be at rest and the test run ends.
c) T-test: The first and last 25 data points in the batch are processed as two populations of measurements on which the t-test is applied. The t-metric is then computed:

$$t = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$$

where t is the t-metric, μ are the means of the two populations, σ their variances and n the number of samples in each population.
The test ends when a batch featuring a t-metric below the user-defined threshold ('Stop t-metric' field) is obtained.

Note: Regardless of stop condition chosen the volatility module will always obey the 'stop time' condition as a safety precaution.
Note: When choosing a stopping condition from the drop-down menu the relevant stopping condition text fields are highlighted in red.

STDP

Perform Spike-Timing-Dependent Plasticity measurements by iteratively applying a voltage series given by the difference of two pre- and post- synaptic voltage spikes with configurable delay.

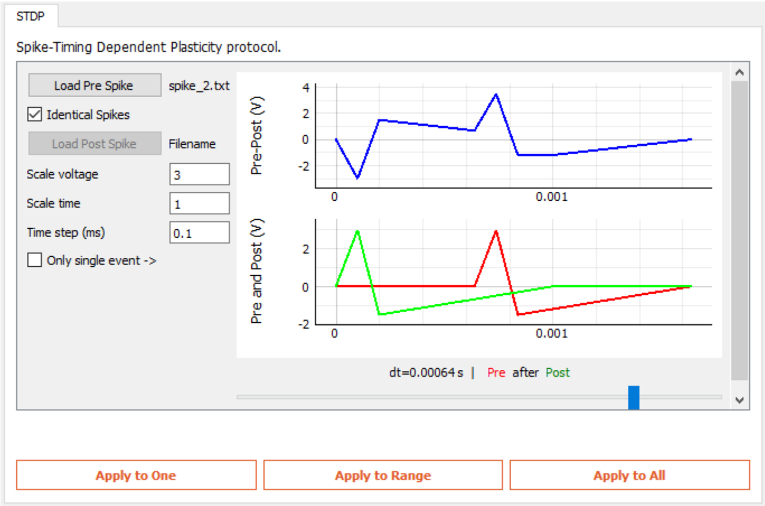


Figure 31: STDP module interface.

Load Pre Spike: browse to load a voltage series text file which will define your Pre- spike. For example, the Pre- and Post- pulses displayed in Figure 31 above were defined in the text file shown on the left. When writing your own spike txt files, make sure the first and last point series has 0V. A few spike txt files can be found in ArC Control/Helper/.

Voltage (V), time (s)

```
0, 0
1, 0.0001
-0.5, 0.0002
0, 0.001
```

spike_2.txt

Identical Spikes checkbox: When checked, the Post- spike will be identical to the Pre- spike. Uncheck to be able to load a different Post- spike.

Load Post Spike: browse to load a voltage series text file which will define your Pre- spike.

Scale voltage and Scale time: scale Pre- and Post- voltage spikes in amplitude and duration.

When a Pre- or Post- voltage spike are loaded, both are plotted on the figure on the right of the module panel. Bottom figure shows both spikes with a corresponding time delay dt, and top figure shows the difference between the Pre- and Post- spikes, which also represents the actual voltage series applied on your test device during an STDP event with that corresponding dt. Move the bottom slider to visualise how the resulting waveform changes with varying dt.

Time step (ms) sets a time step which is used when iterating through STDP events when the experiment is running.

For example in the figure above, Pre- and Post- spikes are identical, and their maximum duration is 1ms. Time step(ms) is set to 0.1ms=100us (henceforth referred to as timeStep). By clicking on Apply to .... the experiment will proceed as follows: First, the resulting waveform of Pre-Post with dt=0s will be applied, followed by the resulting waveform for dt=+timeStep, then for dt=-timeStep, then for dt=+2*timeStep, then for dt=-2*timeStep and so on, until dt becomes greater than the duration of the longest spike (in this case both Pre- and Post- are the same at 1ms).

Only single event checkbox: When checked, only the STDP waveform shown in the top right figure is applied, one time, when clicking Apply to ... . Use this feature to check how a single STDP event might influence the conductance of your device. Uncheck for normal operation like described above.

3.6. SuperMode

SuperMode allows creating chains of measurement modules to better fit your characterisation procedures. Instead of applying consecutive different pulsing modules by hand, simply create an experiment chain with full flexibility.

The module can be found as a bold entry in the drop-down list on the Advanced Modules Panel.

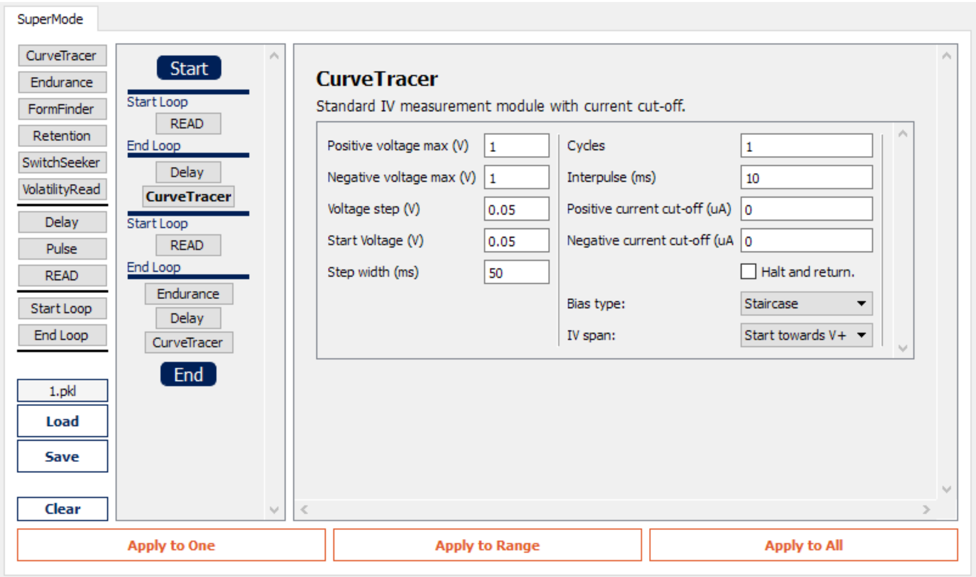


Figure 32: SuperMode panel overview

The left-hand side column contains the available modules built in the platform, along with basic ones such as time delay (Delay), single voltage pulse and single READ operation. Furthermore, Start Loop and End Loop indicators can be utilised as well.

You can drag-and- drop your required modules onto the next column on the right (the chain column), between the blue **Start** and **End** markers. Rearrange them also by drag-and-drop, and discard unwanted ones by dropping them outside the chain column. When applying such an experiment chain to your devices, the instructions will be executed from top to bottom (Start to End).

Double click on a positioned module in the chain column to modify the procedure parameters. The selected module will be highlighted in the chain column. Double click on the Start Loop indicator to set the number of repetitions of the block contained. Nested loops are possible, and the system will check the order of the Start Loop and End Loop indicators for consistency before starting an experiment.

You can Save and later Load measurement chains via the corresponding buttons. The Clear button will delete all entries from the chain column.

4. Example Use Cases

Experimentally demonstrating unsupervised learning with memristive synapses in hardware.
[1] A. Serb, et. al. "Unsupervised learning in probabilistic neural networks with multi-state metal-oxide memristive synapses, Nature Communications, July 2016.

Proving TiOx memristors' capability of integrating bio-signals.
[2] I. Gupta, et. al. "Real-time encoding and compression of neuronal spikes by metal-oxide memristors", Nature Communications, Sept 2016.

A description of a previous version of the instrumentation, and illustrations on utilising the system to interface large memristor crossbars on wafer can be found in:
[3] R. Berdan, A. Serb, A. Khiat, A. Regoutz, C. Papavassiliou and T. Prodromakis, "A ucontroller-based system for interfacing selectorless RRAM crossbar arrays", IEEE Transactions on Electron Devices, 62(7):2190-2196, July 2015.

Characterising volatile behaviour of memristive cells:
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[5] A. Serb, A. Khiat and T. Prodromakis, "An RRAM Biasing Parameter Optimizer", IEEE Transactions on Electron Devices, vol 62, no 11, pp 3685-3691, Nov. 2015.

5. Troubleshooting

5.1. Connection Issues

In the case when the ArC ONE® board does not connect to the ArC GUI, try the following:

1. Make sure the board is powered by checking the LED power indicators.
2. Make sure the board is connected to the PC. A blue LED next to the mBED USB connector should be ON. If the mBED is connected and no blue LEDS are on, contact us.
3. Unplug the USB cable and plug it back in.
4. Restart the GUI (make sure you save any live data).

In the case when the ArC GUI does not receive correct data from the ArC board, save your data, reset the mBED and restart the GUI.

For any other queries, please contact us at: office@arc-instruments.co.uk