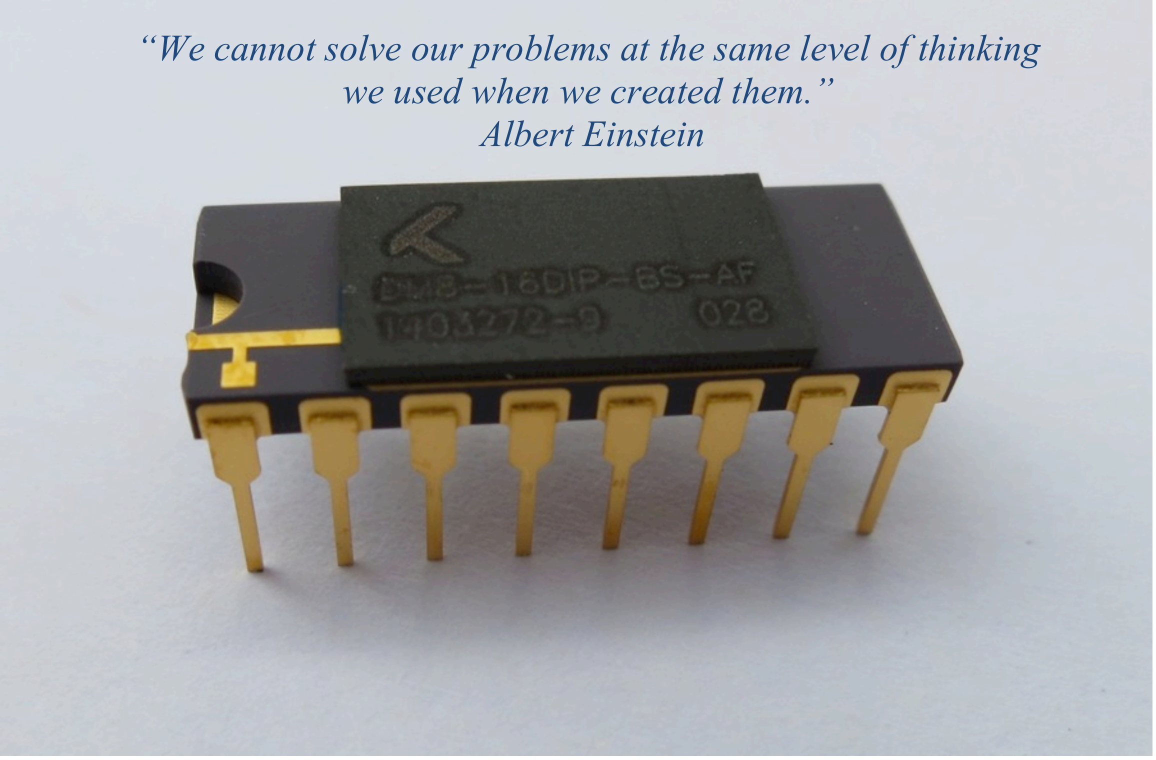
DM8-16DIP-BS-AF-W
Memristors



"We cannot solve our problems at the same level of thinking
we used when we created them."
Albert Einstein

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Read and understand 'warning' section before using or handling!

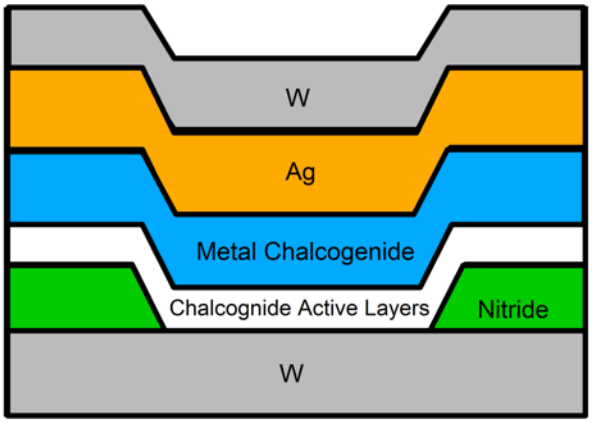
Introduction

A 16-pin ceramic DIP package contains eight (8) discrete memristors. These devices were designed specifically for neuromemristive applications such as AHaH Computing[1], and are capable of continuous resistance switching, ~100 MOhm typical off-state resistance, and bi-directional voltage-dependent pulsed incremental response ideal for learning.

The memristive devices operate primarily through the mechanism of electric field induced generation and movement of metal ions through a multilayer chalcogenide material stack. A secondary mechanism of operation is phase-change, which can be selected as the primary mode of operation depending upon the operating conditions.

Ion Conduction Mechanism

The devices are fabricated with a layer of metal that is easily oxidizable, located near one electrode. When a voltage is applied across the device with the more positive potential on the electrode near this metal layer, the metal is oxidized to form ions. Once formed, the ions move through the device towards the lower potential electrode. The ions move through layers of amorphous chalcogenide materials (the active layers) to reach the lower potential electrode where they are reduced to their metallic form and eventually form a conductive pathway between both electrodes that spans the active material layer, lowering the device resistance. Reversing the polarity of the applied potential causes metal ions to form from the conductive channel and to migrate towards the more negative electrode again, thus altering (increasing) the resistance of the conductive channel. In the ion conducting operational mode, the device is polar, and will cycle between higher and lower resistance values by switching the polarity of the applied potential. The resistance is related at any time to the amount of metal located within the active layer.



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[1] Nugent, Michael Alexander, and Timothy Wesley Molter. "AHaH computing-from metastable switches to attractors to machine learning." *PloS one* 9.2 (2014): e85175.

Symbol and Polarity Conventions

This symbol is used within the Knowm Development Community (KDC) as it is easier to draw by hand and more accurately represents the definition of a memristor. As Leon Chua, the theoretical inventor of the memristor, has said:

"If it's pinched its a memristor"

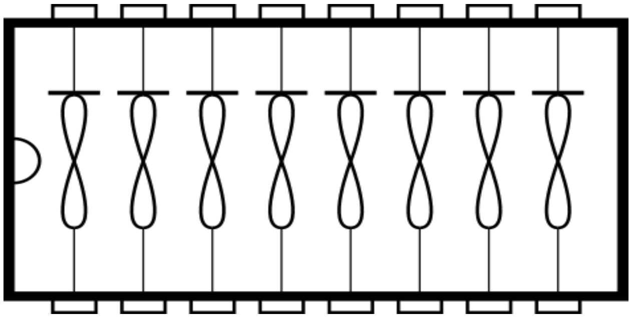
We liked Dr. Chua's definition, but we did not like the symbol. To convince yourself, draw it on the white-board 10 times. Then draw the other symbol. Use it if you like it!

The bar signifies the electrode adjacent to the active chalcogenide layers. In the pristine device, this is the layer furthest away from the original Ag layer. While in ion-conduction mode, a voltage applied across the device with the lower-potential end on the side of the bar, will drive the device into a high conductance state.[2]

From an electrochemistry merged with a semiconductor devices perspective, we believe having the bar on the cathode makes the most since this is where reduction occurs.

Package

16 Pin Ceramic DIP (Dual Inline Package), ideal for breadboard circuit testing.



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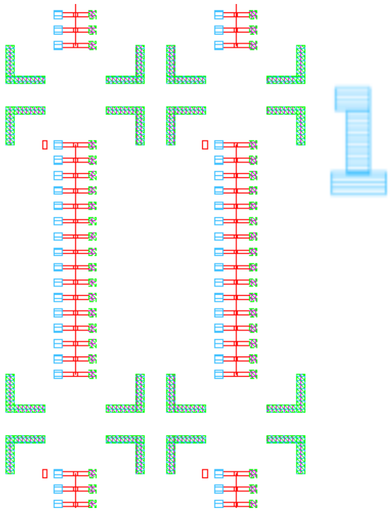
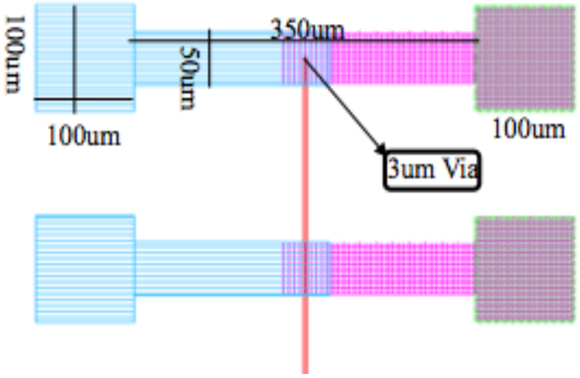
[2] If device has been cycled into and out of Phase Change mode the polarity of the device (in Ion Conduction mode) may be reversed. See Warning section.

Die Layout





Dies are probable and contain 16 discrete two-terminal devices of size 550X100 µm arrayed in one column with 100 µm pitch. Bonding pads are tungsten. The pads on the left column (headed by the number 1) are sputtered over glass and consequently are thinner and fragile, approximately 350 angstroms thick. The pads on the right are CVD tungsten and much more durable.

Electrical Characteristics (25° C)

Characteristic	Condition	Min	Typ	Max
Forward Adaptation Threshold Voltage (V)[1]		0.1	0.18	0.6
Reverse Adaptation Threshold Voltage (V)[1]		-0.02	-0.06	-0.3
Cycle Endurance	1.5 V_{pp}, 500 Hz sinewave, 50 kΩ Series resistor	50M	100M	5B
Forward Pulsed Adaptation Threshold Voltage (V)[2]	500 ns pulse width	0.5	0.6	0.8
Reverse Pulsed Adaptation Threshold Voltage (V)[2]	500 ns pulse width	-0.1	-0.3	-1.5
Pulse Width (s)		10E-9	100E-9	10E0
Current (A)		10E-9	1E-6	100E-6

[1] Under DC, quasi-static, test conditions.

[2] Higher potentials can lead to phase-change operation. See Warnings section.

Maximum Ratings (25° C)

Maximum Ion-Conducting Forward Voltage[3]	1 V
Maximum Ion-Conducting Reverse Voltage[3]	-1.2 V
Maximum Current[4]	0.2 mA
Maximum Sustained Temperature	80 °C

[3] Recommendations are for DC conditions.

[4] Higher current can be used under CW or pulsed conditions, but device operation degrades and the number of cycles attainable is reduced.

Warnings

Static sensitive

Devices are sensitive to electrostatic discharge. Please use accepted methods for handling static-sensitive devices including anti-static packaging, work-surfaces, wrist straps, etc. Do not touch the package leads without taking precautions against electrostatic discharge. Devices will be irreversibly damaged if these precautions are not observed.

Do not measure resistance with a multi-meter

Due to high open-circuit voltages, multi-meters will damage the devices.

Limit Device Current

Set a compliance current or use series resistance. A forward applied voltage will cause devices to enter a very low-resistance state and consequently burn out.

Limit Applied Voltage

Formed devices change resistance between 0.1 and 0.25 Volts and are intended to be normally operated under 1V. High voltages may induce (reversible) phase-change or (non-reversible) damage.

Devices Must be Formed

Your devices may not have been pre-formed when delivered. Forming entails applying a gradually increasing voltage, while limiting current, until the necessary conductive pathways have formed.

Forming Method 1

Apply a DC sweep with a semiconductor parameter analyzer using a 0 to +1 V voltage variable sweep (with a compliance current of 1 μA).

Forming Method 2

Aapply a sinewave input and gradually increase the amplitude of the sinewave until the device responds. To apply the sinewave to the device safely, build a circuit as shown below with the memristor in series with a current-limiting resistor greater than 1 kΩ. As shown in Figure 1, use an oscilloscope to measure at points Px and Py and place oscilloscope into "xy" mode. Apply a 100 Hz sinewave with an amplitude of 0.5 V_{pp}. Gradually increase the voltage until a hysteresis loop is visible. The device is now formed. Decrease the voltage until the hysteresis loop disappears and then gradually increase the voltage again until a hysteresis loop re-appears. If the device had not previously been formed for you, the voltage at which the hysteresis loop reappears will be less than the voltage needed for forming.

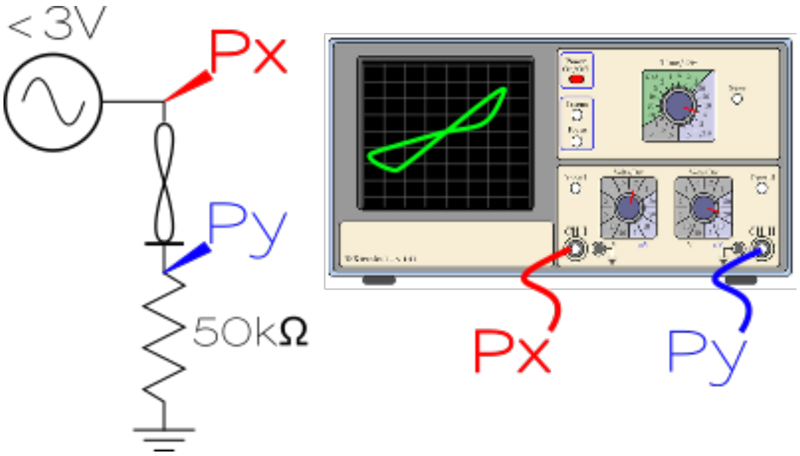


Figure 1: Forming and demonstration circuit

An example of the type of waveform you can expect on Px and Py is shown in Figure 2. Since the device is operating in ion-conduction mode, the voltage across the load responds by following the input waveform during the positive cycle, and during the negative-going erase cycle until the erase threshold causes the device resistance to increase (the 'spike' in the negative portion of Py waveform).

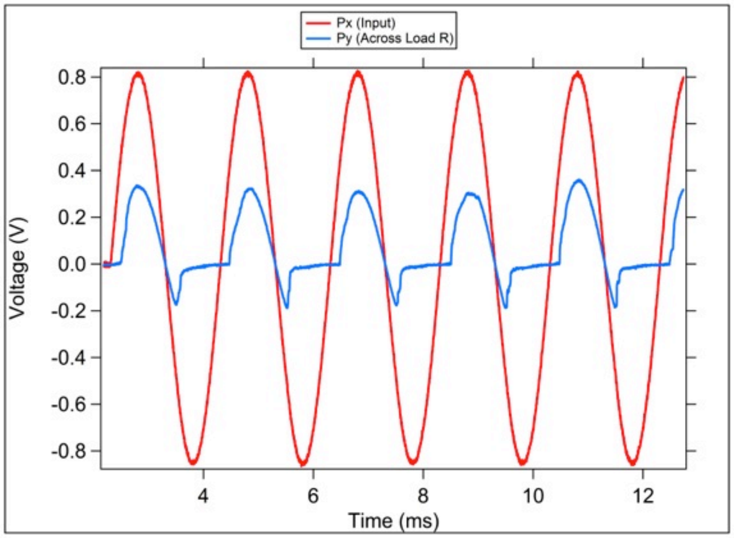


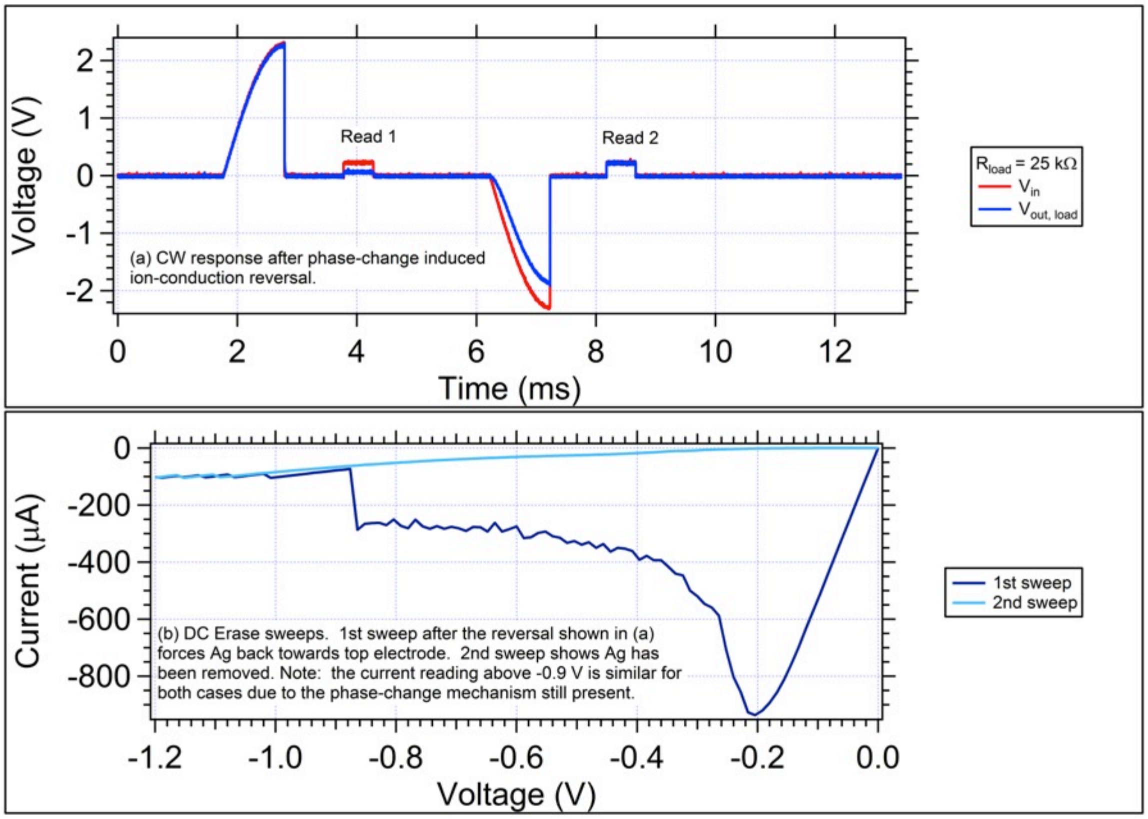
Figure 2: Ion-conduction mode cycling. The Py waveform allows observation of the device response to the input. The positive portion of the input sinewave causes the device resistance to drop. The negative portion causes the device resistance to increase once the erase threshold is reached (shown by the 'spike' in the Py trace).

High Voltage Operation Leads to Phase Change Behavior

Phase-change operation can only occur after the device has previously been operated at least once in the ion conduction mode because there is a permanent material change in the active layers that occurs upon ion conduction. To achieve phase change operation, the device is operated under higher voltage and current conditions. Typical phase-change device melt-quench operating procedures should be used to increase resistance when in this mode. Additionally, this mode allows single polarity operation, if desired. To get the device out of phase-change mode apply a short, higher voltage, melt and quench pulse.

A word of caution when switching between phase-change and ion-conducting operational modes: the device can ‘switch’ polarity in the ion conducting mode when the operational mode goes from phase-change back to ion conduction. This means that the voltage polarities needed at the electrodes in order to increase the resistance are opposite from what they were initially. The ion conduction polarity switch occurs especially if the phase change operation applied a positive potential pulse to the device top electrode. In this case, the ion-conducting mode will operate as if the excess silver layer has moved towards the original bottom electrode. Application of pulses or a DC sweep to drive the silver back towards the top electrode will return the device to its original operating polarity.

An example of this polarity switch is shown in Figure 3. In (a), the device has been placed in a dual phase-change and ion-conduction operational mode and has switched ion-conduction voltage polarities. The fast falling edge of the first pulse removes most of the phase-change crystallinity, but not all, as can be seen by the amplitude of the Read 1 pulse at the output, which is reduced, but not zero as would be expected if all of the crystallinity were removed. The negative going pulse now writes the device to a low resistance, as indicated by the increased amplitude of the Read 2 pulse at the output. The ion-conduction behavior is confirmed with a negative voltage DC sweep, shown in Figure 3 (b) which was taken directly following the programming pulses shown in Figure 3 (a). The device is in a low resistance state and the negative DC sweep moves Ag back towards the top electrode and increases the device resistance. However, the remaining phase-change response is still indicated clearly between approximately -0.9 and -1.2 V in Figure 3 (b), where the current through the device is greater than 100 μA. Note: In Fiigure 3 (a) the high voltages used in the measurement contributed to the phase-change operational mode.



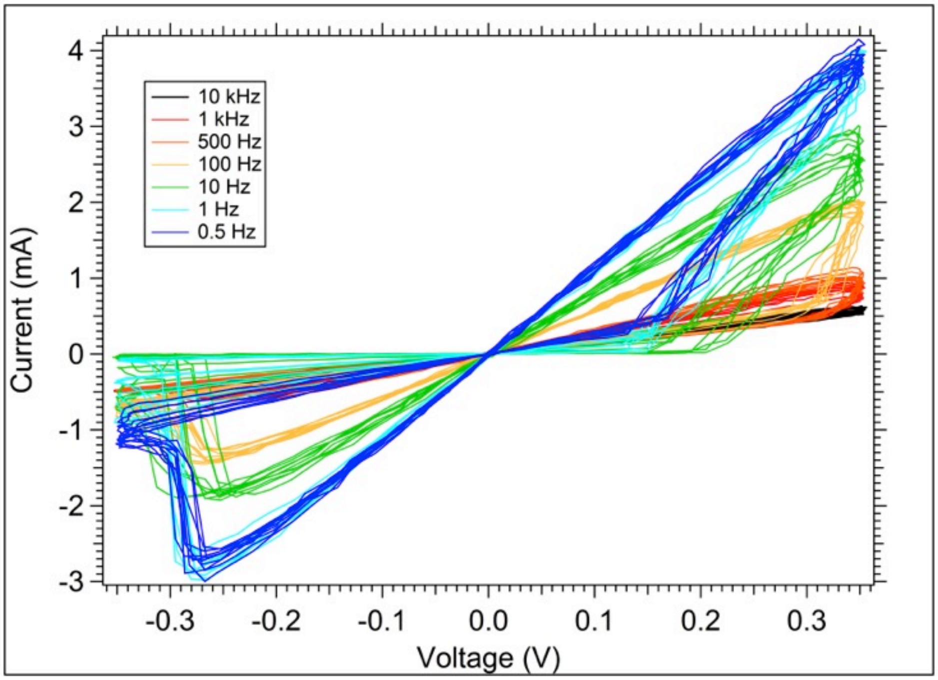
(a) CW response after phase-change induced ion-conduction reversal.

(b) DC Erase sweeps. 1st sweep after the reversal shown in (a) forces Ag back towards top electrode. 2nd sweep shows Ag has been removed. Note: the current reading above -0.9 V is similar for both cases due to the phase-change mechanism still present.

Figure 3: A device operating with both the phase-change and ion-conducting mechanisms. (a) CW response showing the device writing to a low resistance with the negative (switched polarity) pulse. (b) DC sweep erases the device and returns ion-conducting polarity to the standard operating mode. Phase-change mode is still present as can be seen by the large current at the higher negative potentials.

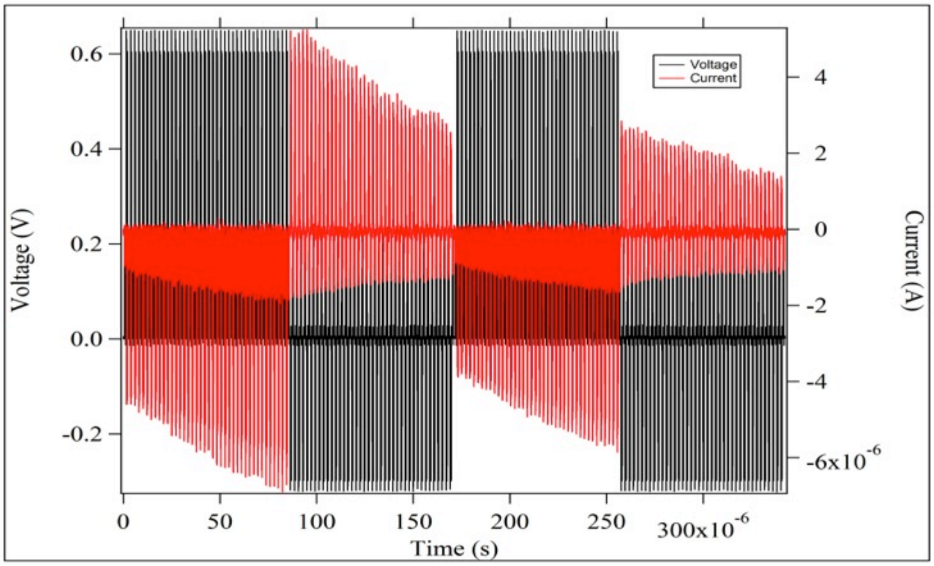
Typical Responses

Sine Wave Input Frequency Response

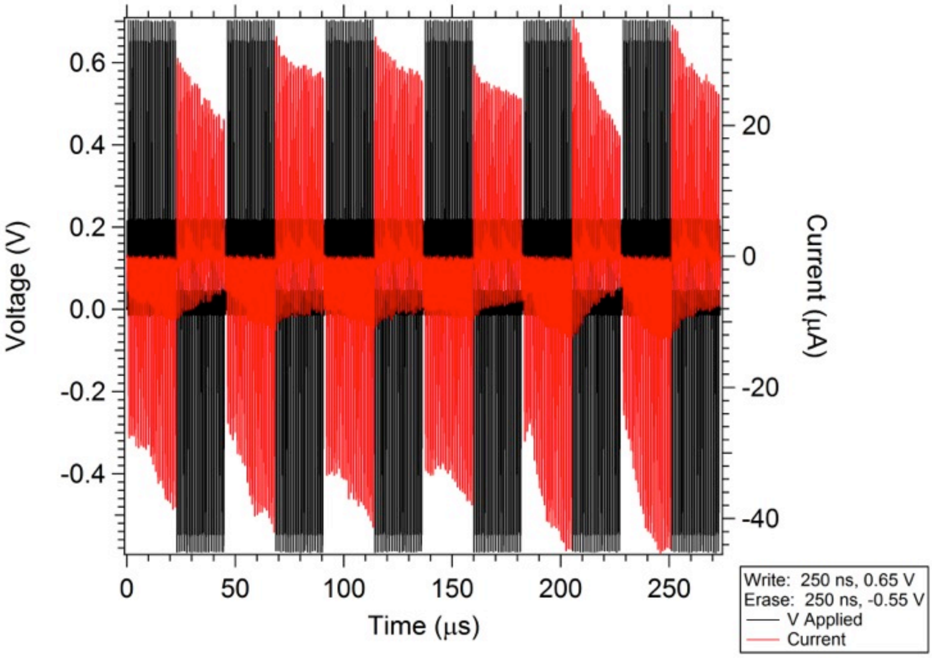


Note: Current allowed through the device in this frequency measurement is higher than that recommended for maximum cycle endurance.

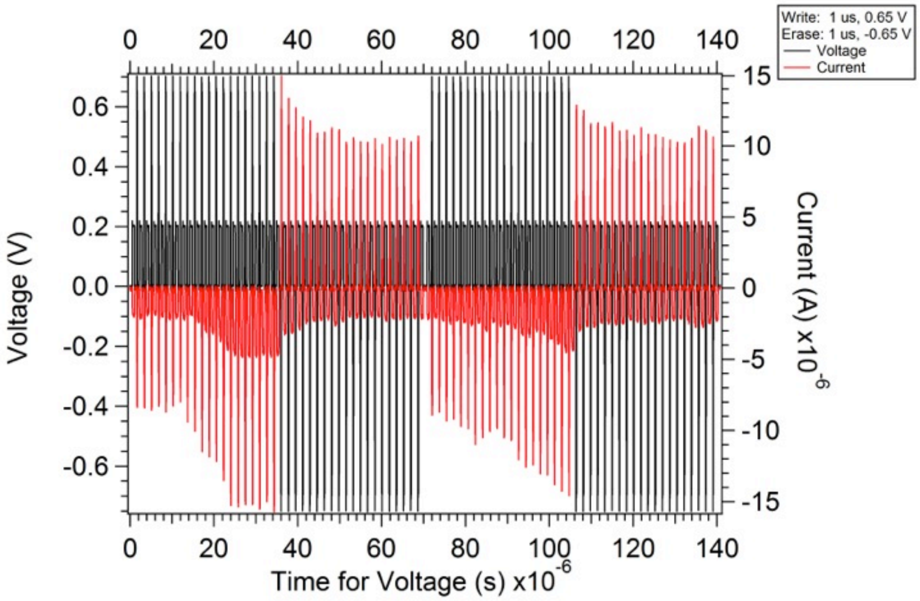
Constant Low-Amplitude Pulses (500ns)



Constant Low-Amplitude Pulses (250ns)



Constant Low-Amplitude Pulses (1µs)



Variable Voltage Pulses (500ns & 100ns)