Microsystems
Science, Technology & Components

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Characterizing Switching Variability in TaO_x Resistive Memories

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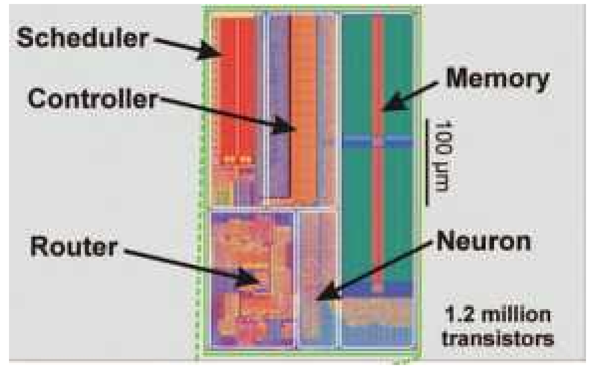
Neural-inspired Computing Hardware

Mark I Perceptron (Rosenblatt 1960):

Arvin Calspan Advanced Technology Center; Hecht-Nielsen, R. *Neurocomputing* (Reading, Mass.: Addison-Wesley, 1990); Cornell Library;

DARPA , IBM TrueNorth (2014):

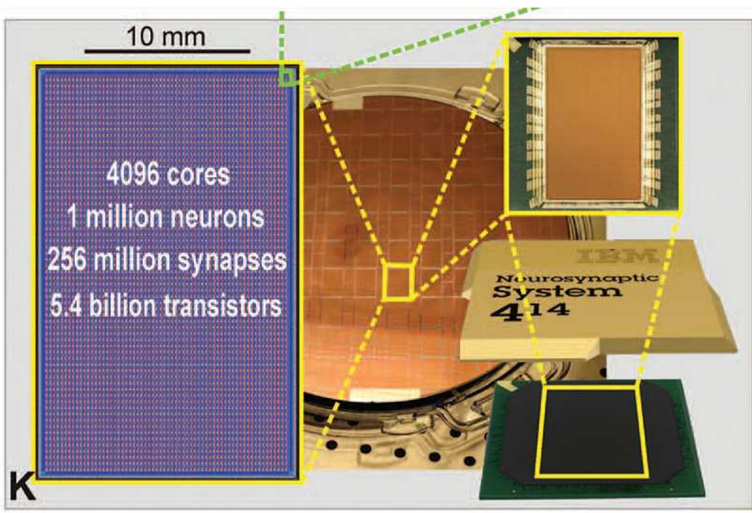


EU HBP, SpiNNaker (2014):

?

Current State of the Art in Neural Algorithm Computing

- CPU/GPU
  - Most general; common programming languages
  - Lowest power efficiency and performance
  - Memory separate from chip
  - Example: Google deep learning study (CPU→GPU)
- FPGA
  - General; requires hardware design language
  - Moderate performance and efficiency
- Custom IC (Truenorth, Spinnaker)
  - Specific: ex. executes STDP
  - Highest performance and efficiency
  - Expensive, 40MB local memory
  - Example: IBM Truenorth
- Moore law has provided enormous benefits to all of these technologies



Why Do We Need an HW Accelerator?

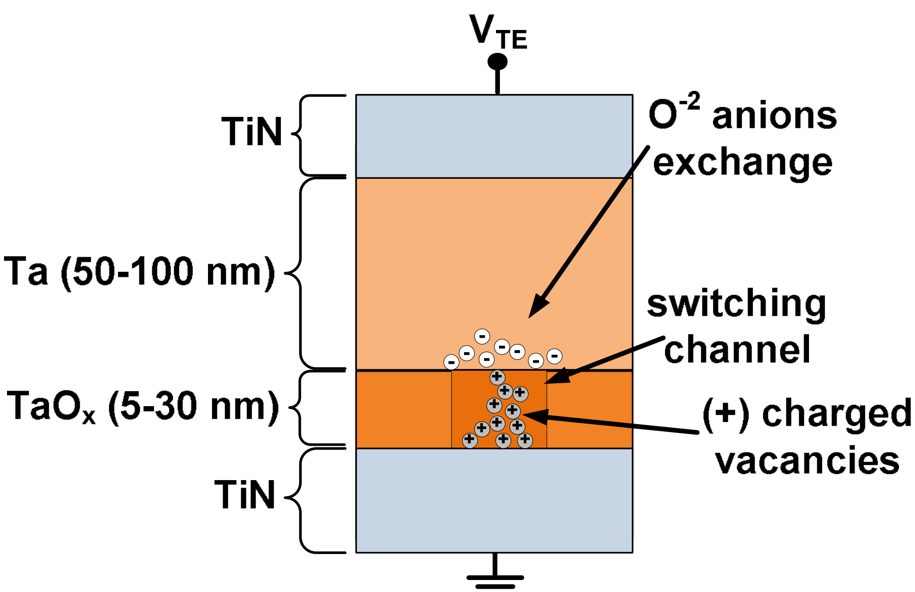
- **Problem: perceptron network training slow and extremely computationally intensive**
- Use simulation results for similar algorithm as example
- Significant power savings using a memristor-based HW accelerator :
- 16x reduction in power over SRAM ASIC
- 6x reduction in chip area over SRAM ASIC
  - Equivalent to 6x improvement in performance/area

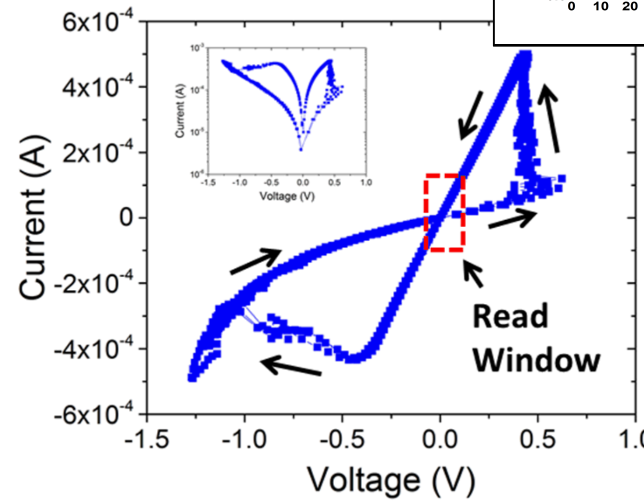
	Example 1: 25,600 neurons 100,000 iterations/s				
Configuration	# of chips	Chip area (mm^2)	% active	Power (W)	**Power eff. over Xeon**
Memristor Analog (config 4)	1	5.9	38.6%	0.07	**234,859**
Memristor Digital (config 5)	1	18.2	89.6%	0.62	**16,968**
SRAM (config 6)	1	29.1	89.6%	1.13	**8,215**
NVIDIA M2070	12	529.0	99.2%	2700.00	**6**
Intel Xeon X5650	179	240.0	99.9%	17005.00	**1**

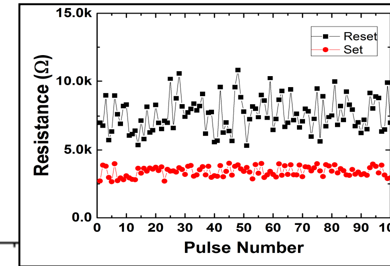
T. Taha, et al. IEEE IJCNN 2013.

Memristor I-V Characteristics

- Resistive RAM stores state in the form of resistance
- Applied current and voltage can change resistance state
  - Hysteresis loop
- Low voltages can read state
  - Read window





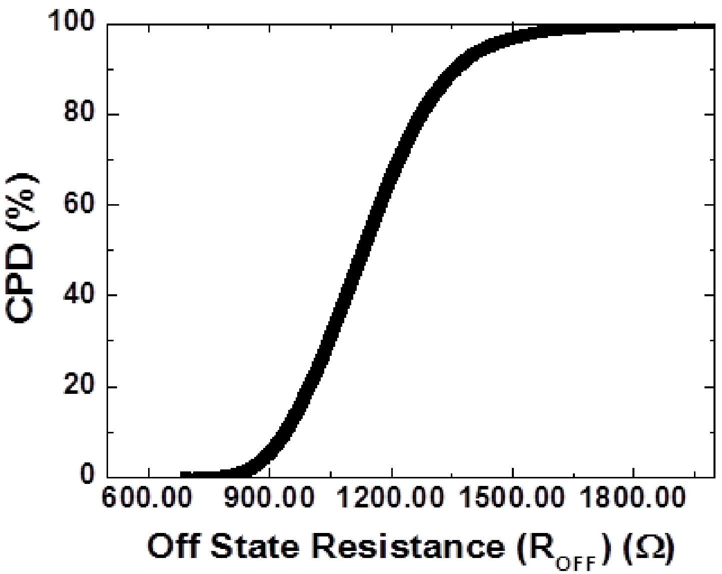


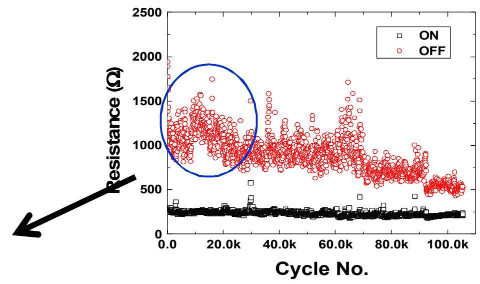
- Resistive switching
  - Oxygen vacancies
- TaO_x
  - Oxygen anions

Variability and Noise

- **Interdevice variability**: device to device, can be >10x
  - Variations in film thickness, topography
- **Intradevice variability**: cycle to cycle, can be >2x
  - Fundamental physical attributes
- **Random telegraph noise:**
  - Affects read current

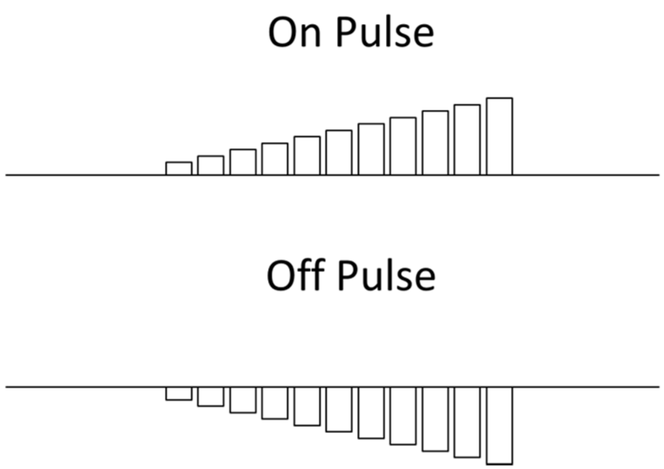
- Characterizing cycle to cycle variability is essential for future neuromorphic applications





Testing Algorithms

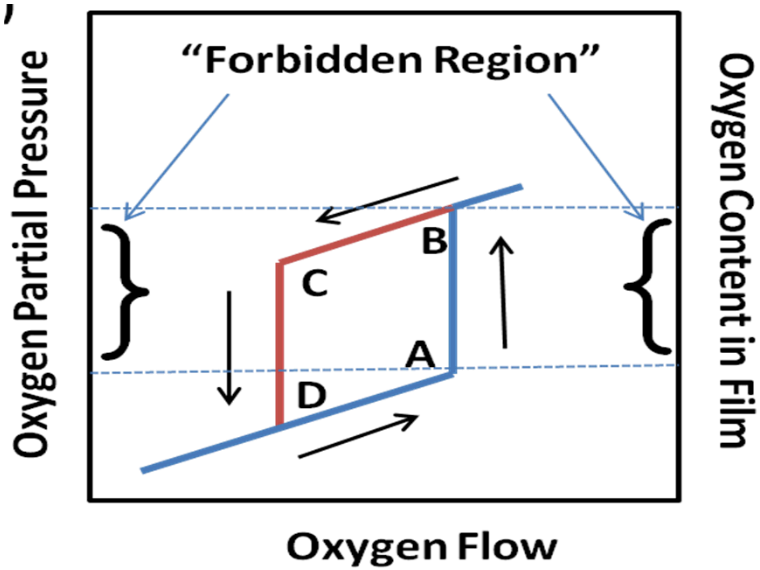
- An automated test algorithm has been developed to form, reset, and cycle devices with gradually increasing pulse heights
- The algorithm can be programmed to target specific resistances, stopping once a particular resistance threshold is reached



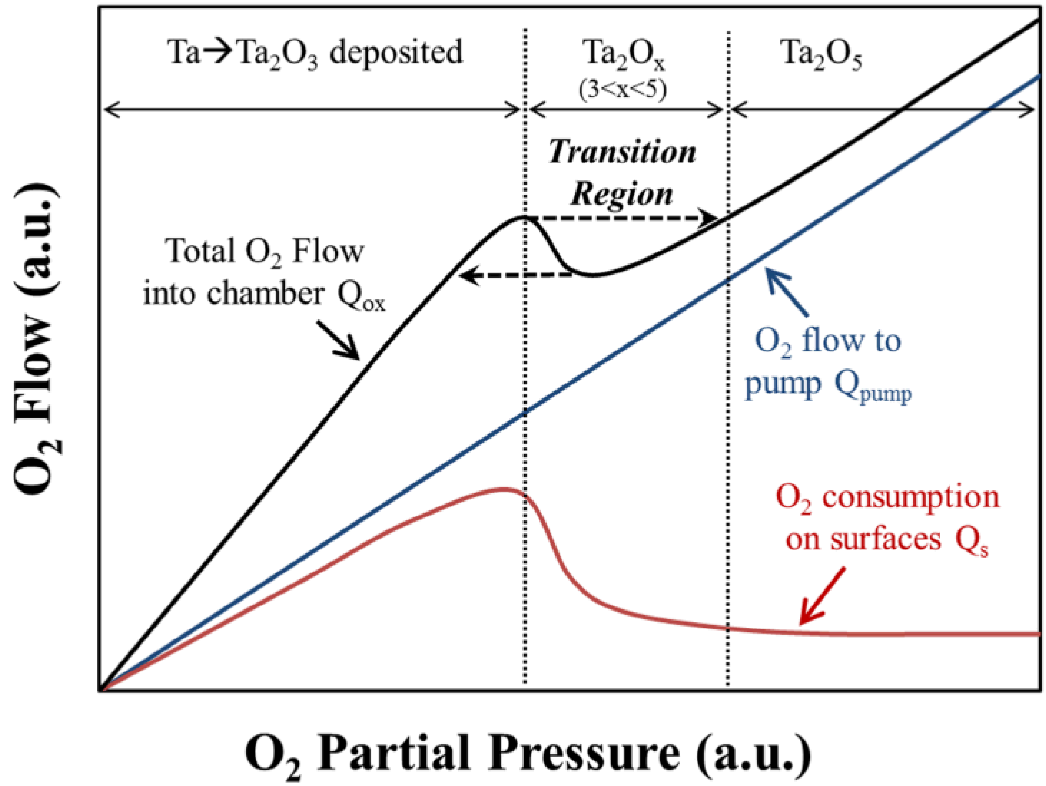
- Evaluate the effects of process changes like thickness and stoichiometry to optimize future devices for the targeted characteristics
  - Multi-state suitability

Switching Film Development: Overcoming the "Forbidden Region"

- One of the parameters that we vary is oxygen content
- Forbidden oxygen flow-pressure region occurs due to target poisoning
  - This is the region we need to be in to get ideal ReRAM stoichiometry



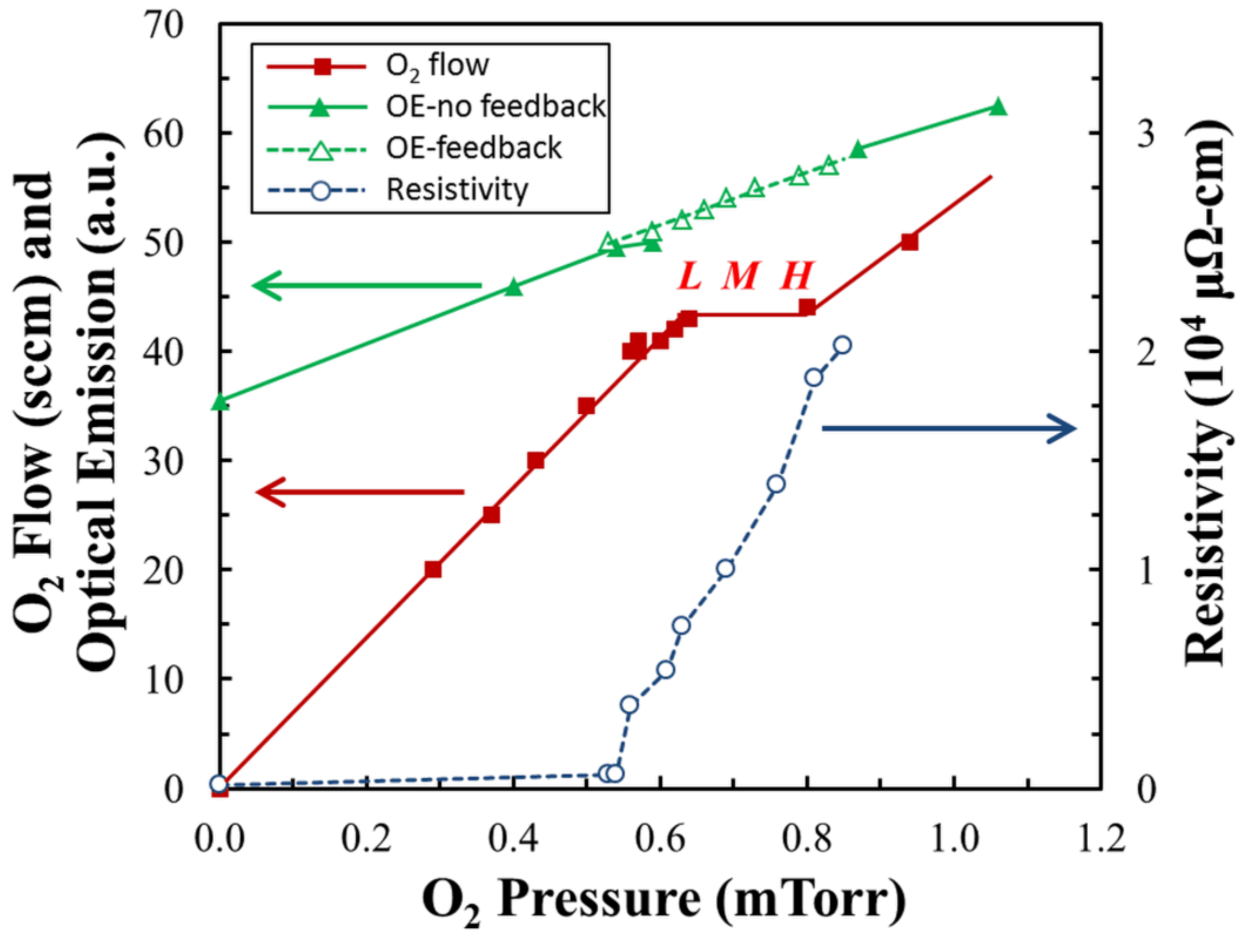
A.J. Lohn et al APL 103, 063502 (2013)



J.E. Stevens et al, J. Vac. Sci. Technol. A 32, 021501 (2014)

Solution: Feedback System

- **Penning gauge measures oxygen partial pressure**
- **Real time feedback to oxygen flow control**
- **Elimination of Forbidden Region!**



J.E. Stevens et al, J. Vac. Sci. Technol. A 32, 021501 (2014)

Effect on Device Behavior

Fraction of "forbidden region"	Partial pressure set #1	x: Ta_2O_x set #1	Yield (%)	Endurance	Partial pressure set #2	X: Ta_2O_x set #2
0	50.0	1.9 + 0.5	20	~3 cycles	43.0	2.1 + 0.5
1/3	52.5	3.3 + 0.5	80	$>10^4$ cycles	44.6	3.5 + 0.5
2/3	55.0	4.2 + 0.5	0	…	46.2	4.0 + 0.5
1	57.5	4.6 + 0.5	0	…	48.0	4.4 + 0.5
4/3	60.0	5.0 + 0.5	0	…	49.5	5.0 + 0.5

A.J. Lohn et al APL 103, 063502 (2013)

- **Thickness and stoichiometry splits tested for multi-level suitability**
- **Another lot had a range of partial pressures that spanned from 50% to 100% of the forbidden region and a thickness of 8 nm**
  - **No multi-level switching seen**
- **Another lot had a range of oxygen-flow that spanned from 60% to 150% of the forbidden region and thicknesses of 5, 8, and 11 nm**
  - **Only the 11 nm samples showed multi-level switching**
  - **May be due to higher resistance ranges**

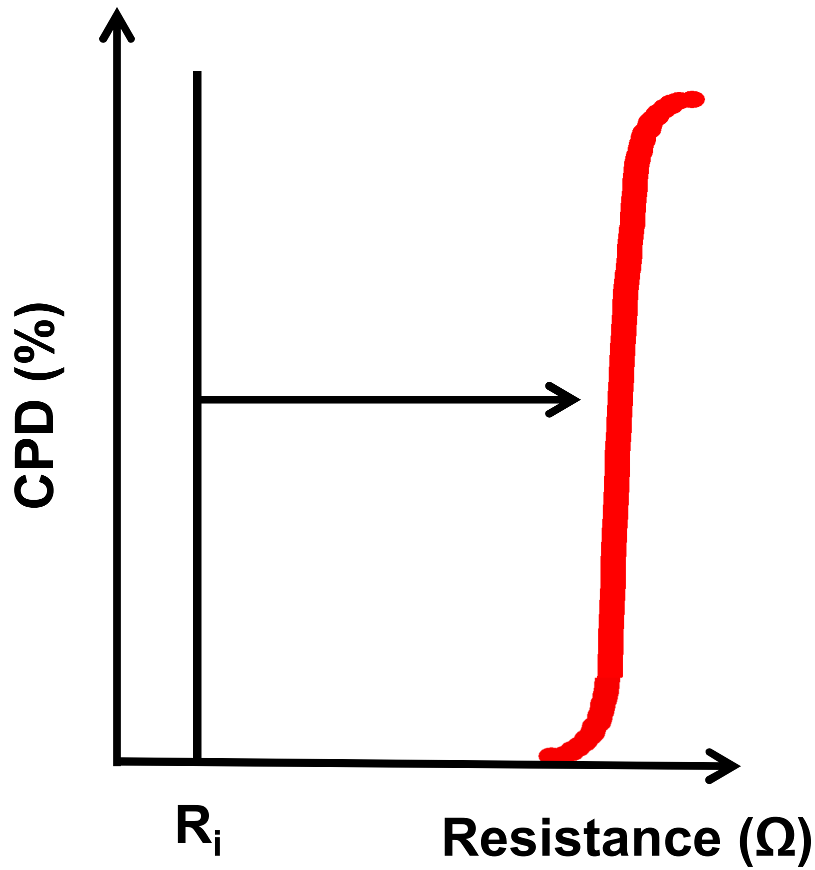
Modeling Variation

- Characterizing cycle to cycle variation can inform models to help predict whether the variation present will be tolerable by neuromorphic algorithms

- Analytical model

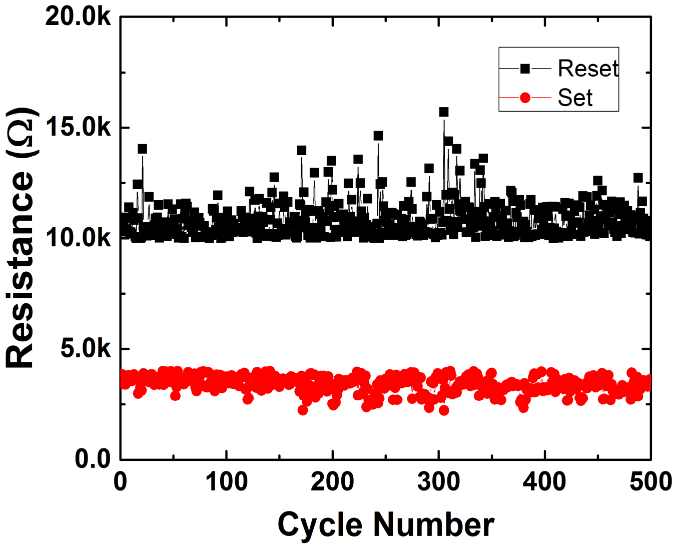
$$R_{final}(V,t) = R_i + R_{avg}(V,t) \pm R_{\sigma}(V,t)$$

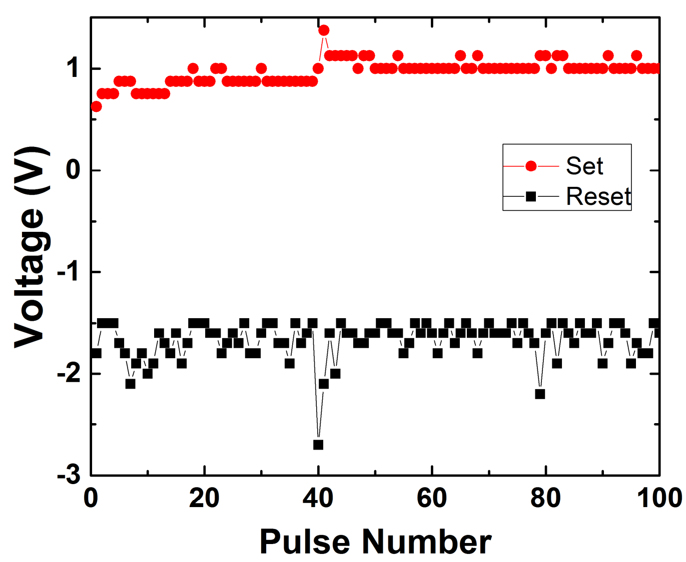
  – Feedback helps to achieve a more consistent R_i



Programming Resistance with Feedback

- Initial tests are run with feedback designed to target specific resistances
  – Useful when characterizing a specific transition
- Voltages are recorded when the resistance threshold is reached
  – Can be used to determine programming pulses for operation without feedback





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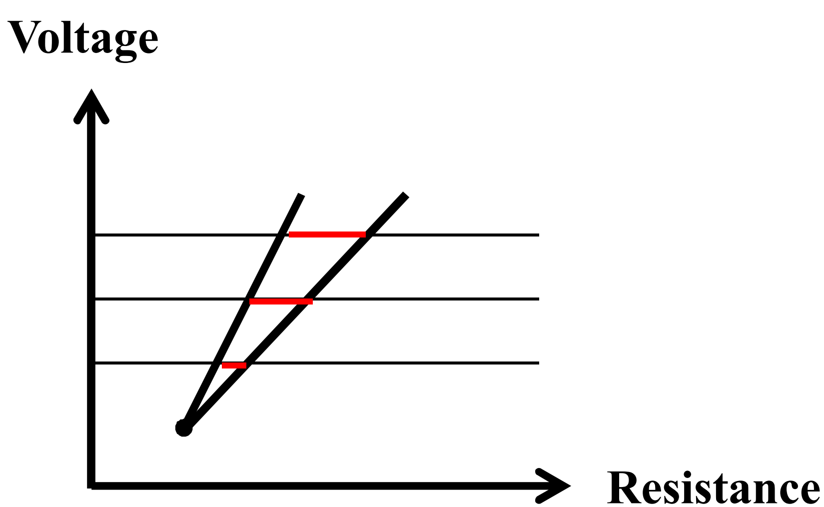
Switching Variation for Multiple States

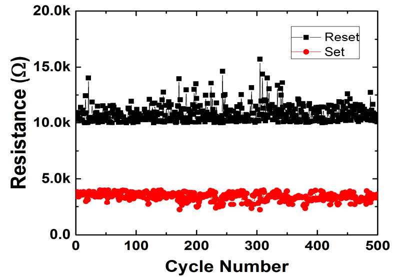
- One concern is how the variation changes when switching between multiple potential states
  - Does it vary based on the magnitude of the switch?



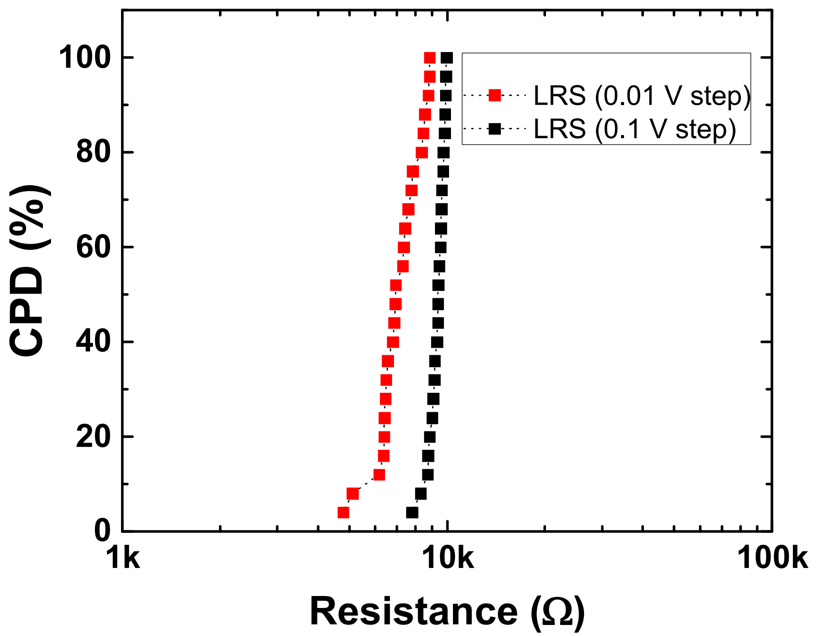
- To investigate, devices were programmed to a specific on-state resistance and programmed with a single reset pulse to multiple levels

Voltage Step Size

- The voltage step size used to program the on-state for the results in this talk was 0.1 V



- A finer step size was tested to see if the resistance distribution would be better



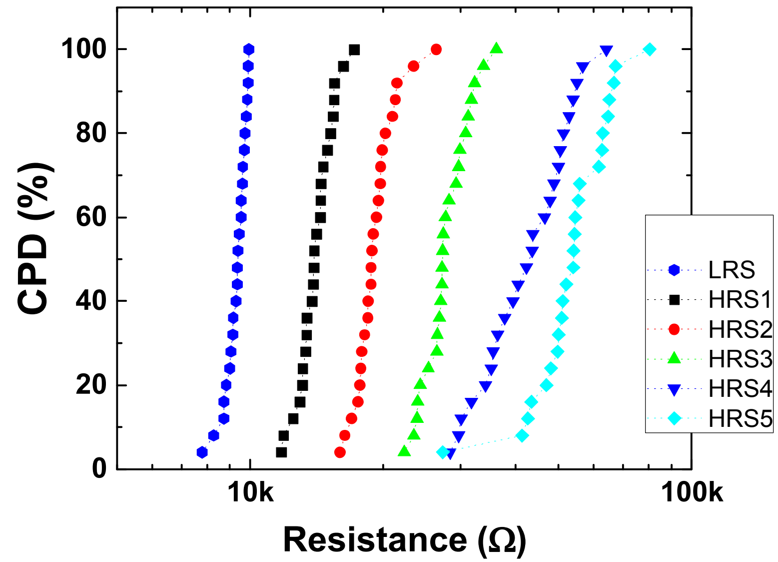
- The larger step size actually showed a larger distribution
  - Device quality likely a larger factor in this regime than voltage step size

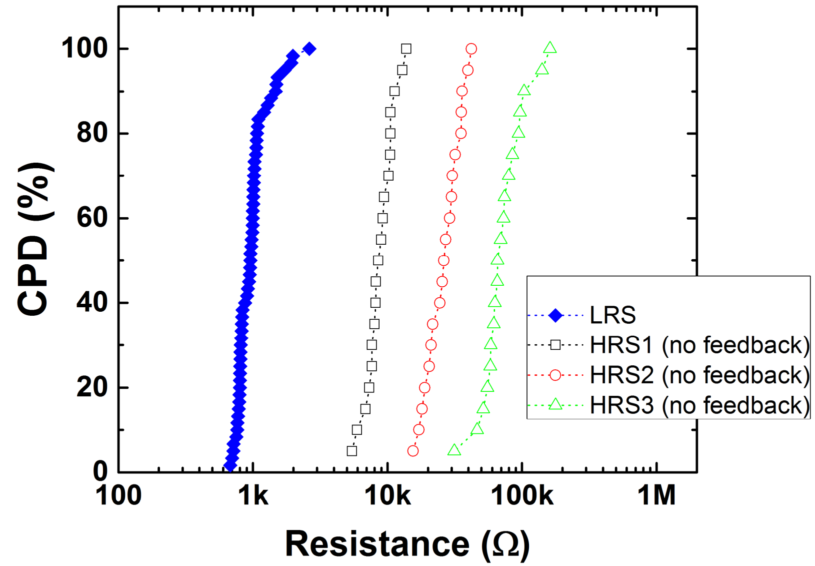
Multi-State Operation

- Devices were cycled with feedback to get the initial reset voltage, which was increased by -0.25 V for each test

- Targeted resistances for all levels also possible

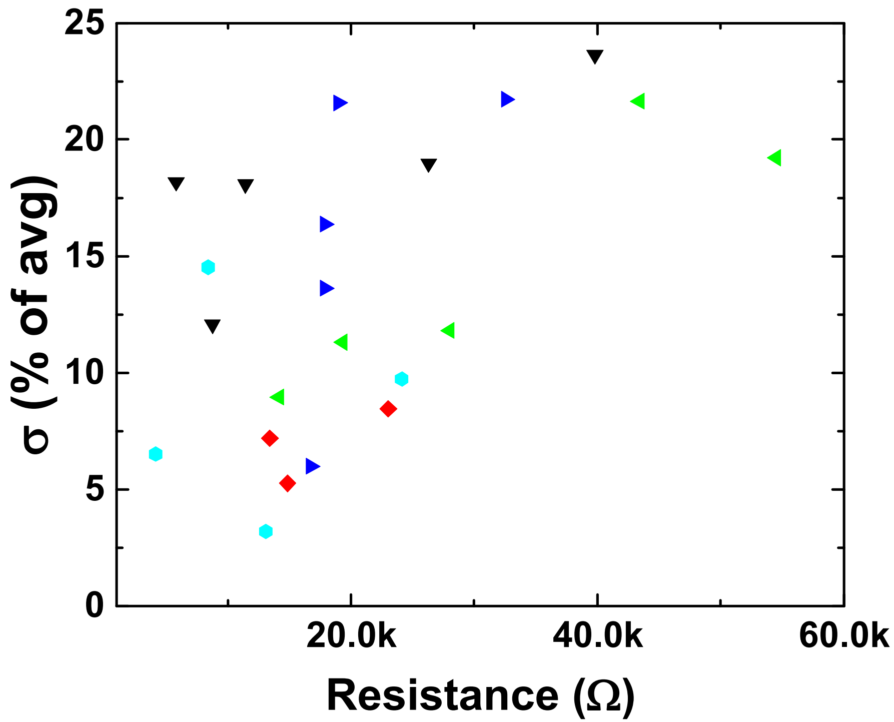
- Future tests will continue to investigate devices with different combinations of thickness and oxygen content to optimize multi-level switching





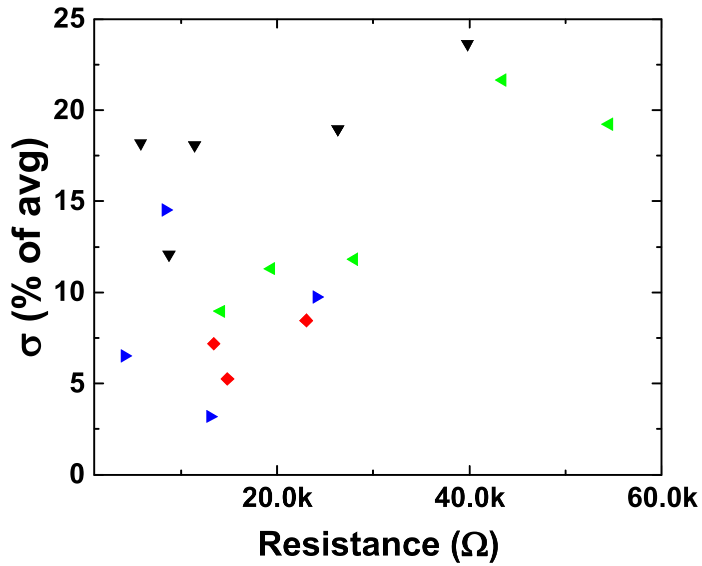
Variability at Different Resistances

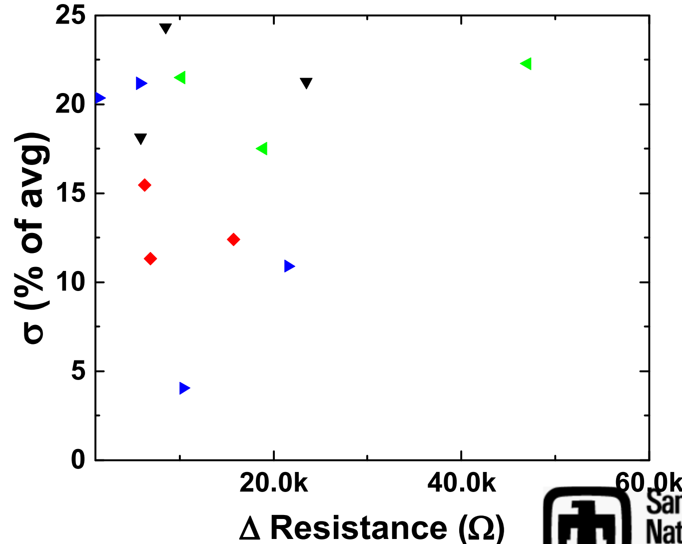
- The standard deviation as a percentage of the average resistance has been plotted at various resistances
- Initial data suggests that the variability in switching increases as the resistance increases
  - Fewer critical defects?
  - It may be easier to create more discrete states at lower resistances



Variability at Different Resistances

- The standard deviation as a percentage of the average resistance increases with increasing resistance
  - Not with magnitude of resistance change
- Initial data suggests that the variability in switching increases as the resistance increases
  - Fewer critical defects?
  - It may be easier to create more discrete states at lower resistances





Summary

- Feedback algorithms have been used to gather data on cycle to cycle variability
  - Essential for modeling realistic devices for neural algorithms
  - Data collection is ongoing, expanding to include more process variables and programming pulses
- Multiple high resistance states have been demonstrated on TaO_x devices
  - Thicker films show more promise for multi-state operation
  - Higher resistance range will be investigated
  - Multiple methods of multi-state programing
- Cycle to cycle variation tends to increase at higher off-state resistances
  - The number of discrete states may increase when targeting lower resistances