Design and Optimization of TMO-ReRAM Based Synaptic Devices

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Outline

- Introduction
- Physical Mechanism
- Defect Engineering Approach
- Optimization of Synapse
- Summary

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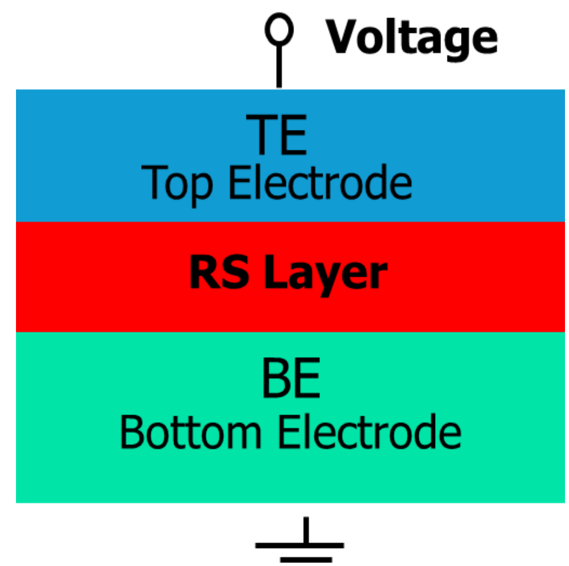
Introduction

Resistive Switching (RS)

- Many materials have been used to demonstrate the reversible bi-stable resistance states (LRS and HRS), which can be switched by voltage, named as ***resistive switching (RS)***

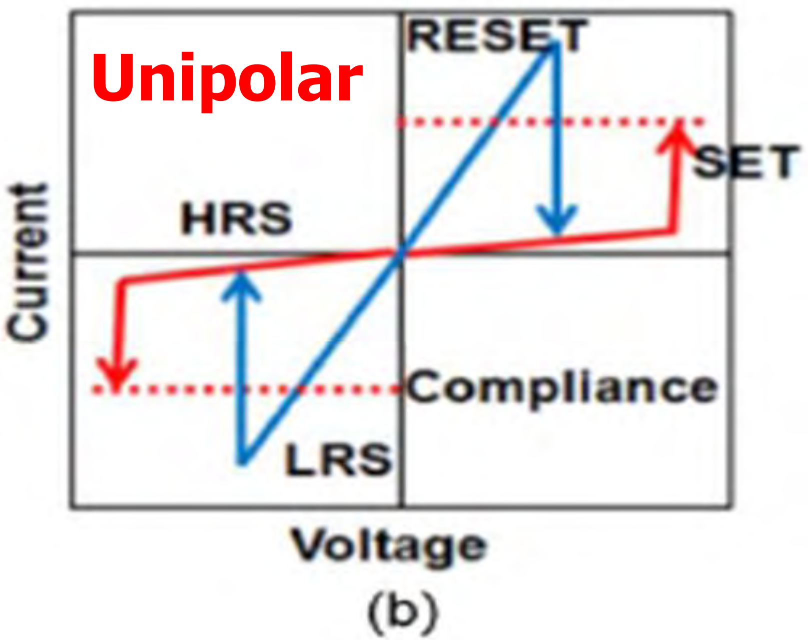
RRAM

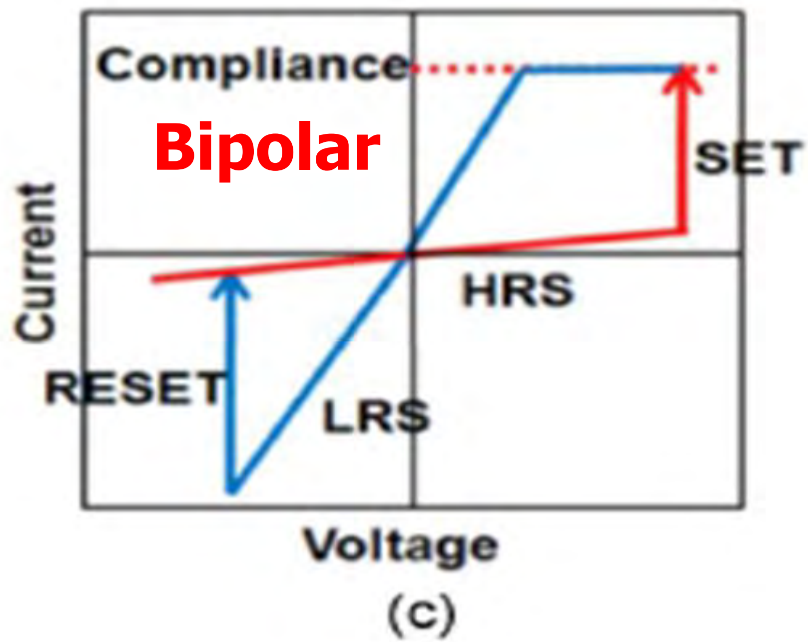
- These RS materials can be used to construct a device, with a typical sandwiched structure, termed as RRAM (Resistive-switching Random Access Memory).



Introduction

Two Switching Modes [#]





depend on amplitude of applied voltage but not on polarity

depend on the polarity of the applied voltage

[#] H.-S. P. Wong et al., Proc. IEEE, 100, p.1951, 2012.

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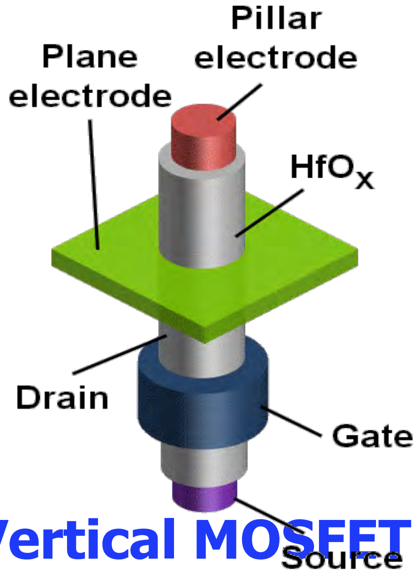
Introduction

- **Excellent performances have been demonstrated in transition metal oxide (TMO)-ReRAM [1-6].**
  - **Scalability:** <10nm devices demonstrated [1-2]
  - **Compatibility with CMOS using fab-friendly materials [1-4]**
    - HfO_2, TaO_x, WO_x, Ti, Ta, TiN, NiSi
  - **Switching speed:** <1ns [6]
  - **Switching voltage:** <1.5V
  - **Endurance:** >10^{10} cycles [5]
  - **Retention:** >10 yrs [6]
  - **Read disturb:** >10^{10} times [3]

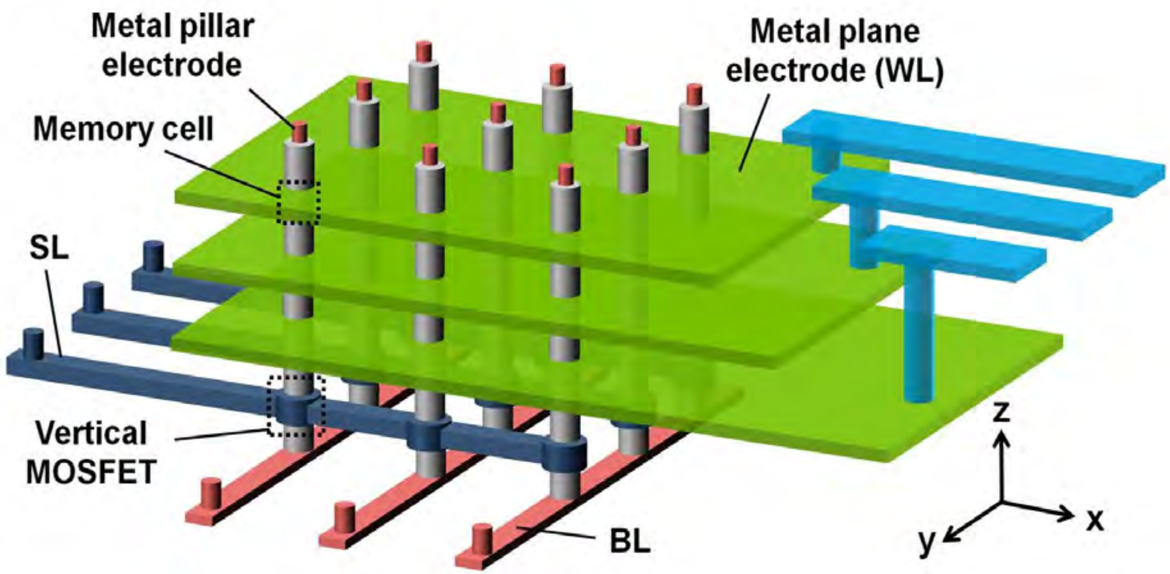
[1] K-S Li et al, VLSI-T2014,
[2] C-W. Hsu et al, IEDM2013
[3] W. Chien et al, IEDM2010.
[4] X.A. Tran et al, IEDM2011
[5] H.Y. Lee et al, IEDM2010.
[6] Y.S.Chen et al, IEDM2009

Introduction

Capability to High Density Integration [1,2]



Vertical MOSFET



✓ **32/16 Gb Test Chips have been demonstrated [3,4]**

[1] H.-Y. Chen, et al., IEDM2012, p.497 (Stanford & PKU);

[2] ITRS 2013, http://www.itrs.net, PIDS Chapter

[3] T-Y Liu et al, ISSCC2013, p493 (Sandisk & Toshiba)

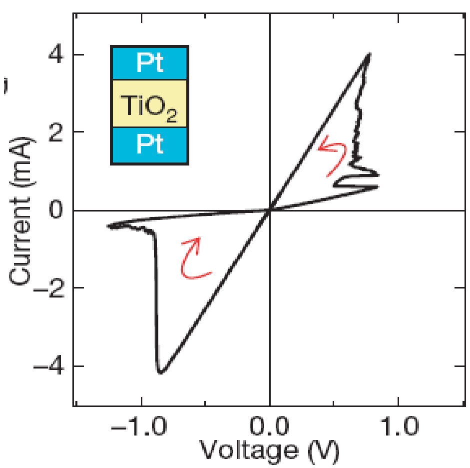
[4] R. Fackenthail, et al, ISSCC2014, p338 (Micron & Sony)

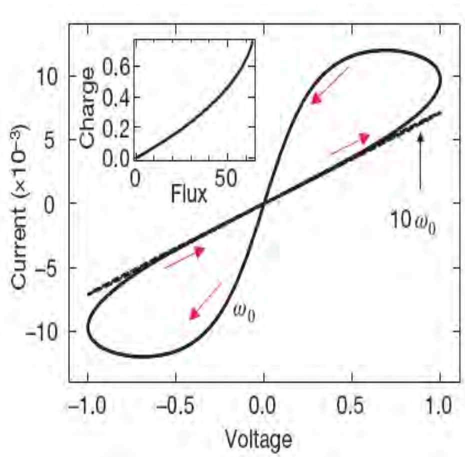
◻ Introduction

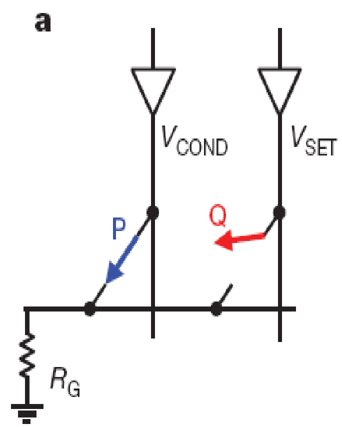
❑ New Function Application

Concept of RRAM based memristor [1]

- Memristive switches: both store logic values and perform logic operations [2]







b

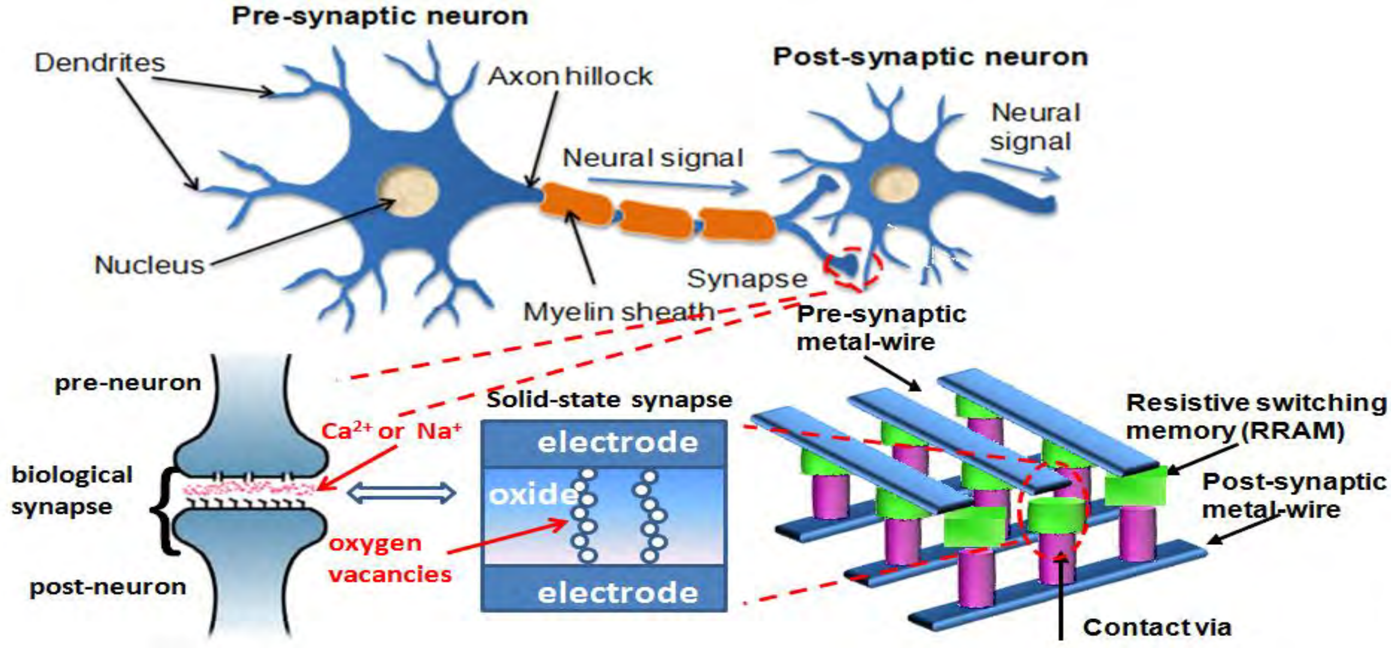
$q' \leftarrow p\text{IMP}q$

In p	In q	Out q'
0	0	1
0	1	1
1	0	0
1	1	1

[1] D. B. Strukov et al, Nature 2008, 453, p.80
[2] J. Borghetti, Nature 2010, 464, p.873-876

□ Introduction

RRAM based synapses for neuromorphic computing systems [#]



[#] S.M. Yu et al, IEDM2012, p.239 (Stanford and PKU)

Most demonstrated in the bipolar switching mode

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□ Introduction

□ For applications

- Understand the physical mechnisms of RS
- Seek technical solutions to construct RRAM devices to achieve targeted performances [1]

❑ In this talk, we will also address

- Low energy and robust synapse performances of TMO-RRAM [2, 3]
- Potential for application in a neuromorphic visual system [2]
- .....

[1] B. Gao, et al. IEEE T-ED, 60(4), pp 1379, 2013;
[2] S. Yu, et al. IEDM 2012, p.239;
[3] B. Gao, et al, ACS Nano, 8, p. 6998, 2014

Outline

- Introduction
- Physical Mechanism
- Defect Engineering Approach
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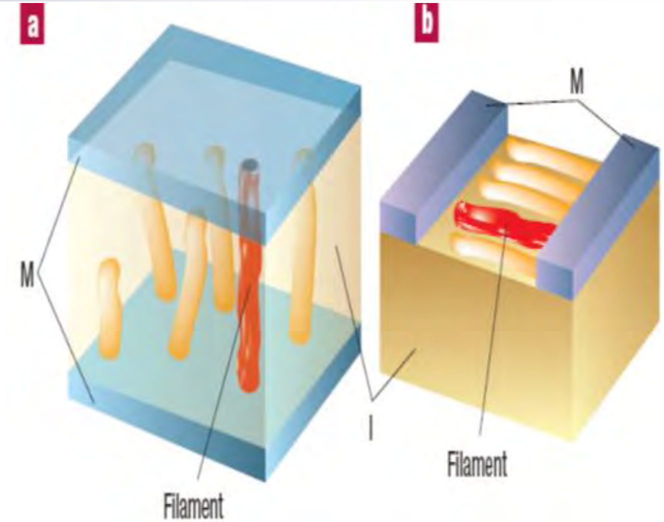
□ Physical Mechanism

- **For the resistive switching (RS) behavior of TMO-RRAM**
  - Filament effect has been widely accepted
    - ➢RS is due to the formation and rupture of conducting filaments



R. Waser, Nature. Mat. 2007

However, the physical natures of filaments and the crucial effects to dominate the formation and rupture of filaments are still argued

- Conducting filament (CF) type: Vo or metallic ions?
- Dominant effect for SET/RESET: G-R or S/D? Thermal or E-field?
- Mechanisms of unipolar and bipolar: Same or not?

□ Physical Mechanism

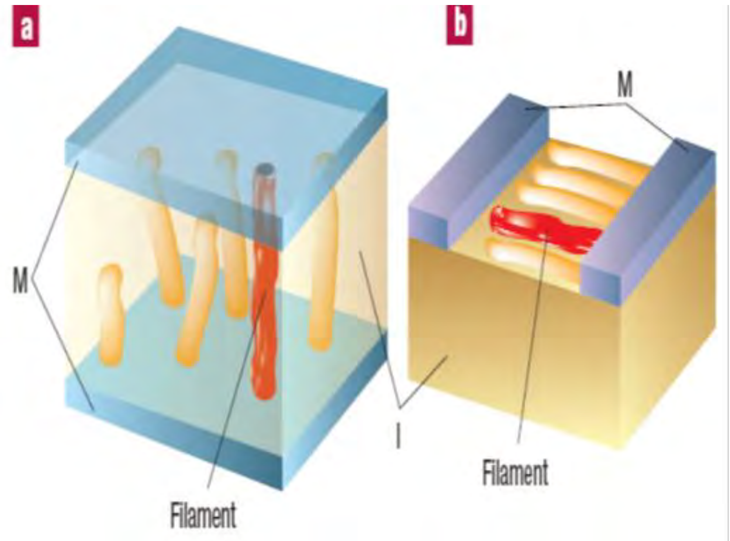
- A Unified Physical Mechanism [1,2]
  - **To clarify fundamental properties of resistive switching behaviors in TMO-ReRAM**

[1] N. Xu et al, VLSI-T 2008, p.100

[2] B. Gao et al, IEDM2011, p.417

- The mechanism is based on filament effect on RS [3]

[3] R. Waser, Nature. Mat. 2007



Unified Physical Mechanism

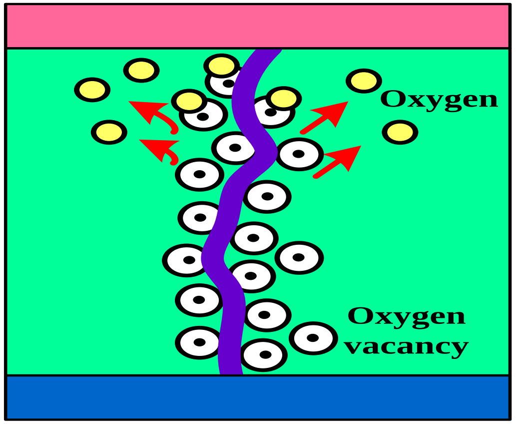
The unified physical mechanism is proposed to clarify these argued issues:

- **Microscopic physical properties correlated with resistive switching in TMO-based RRAM (including unipolar and bipolar)**
  - **To explain various resistive switching characteristics observed in TMO-RRAM**
  - **To predict performances of TMO-RRAM**

Unified Physical Mechanism

Schematic microscopic properties of RS in TMO-RRAM

(B. Gao et al, IEDM2011, p.417)



$$LO \xrightarrow{E-Field} V_O^{2+} + O^{2-}$$

$$V_O^{2+} + 2e^{-} \longrightarrow V_O$$

$$p = \exp[(eLE - \varepsilon_V^f)/kT]$$

$$\bar{N}_V = \frac{t}{t_0} N_{LO} p$$

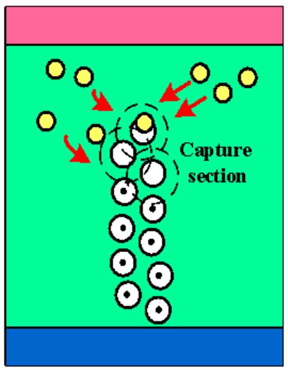
$$\Delta N_V = \sqrt{N_{LO} \frac{t}{t_0} p (1 - \frac{t}{t_0} p)}$$

1. **Filament: A percolation path consisting of V_O defects**
2. **Formation and rupture of filaments are correlated with generation and recombination of V_O**
3. **Forming/SET: Generation of new V_o defects and O^{2-} ions induced by E-field and thermal effects in rupture region**

- **V_o defects may be in different states:**
  - ✓ **Filled state (V_O) with 2 electrons in V_o**
  - ✓ **Unfilled state (V_o^{2+}) w/o electron in V_o**

Unified Physical Mechanism

Schematic microscopic properties of RS in TMO-RRAM



$$V_O \xrightarrow{E-Field} V_O^{2+} + 2e^-$$

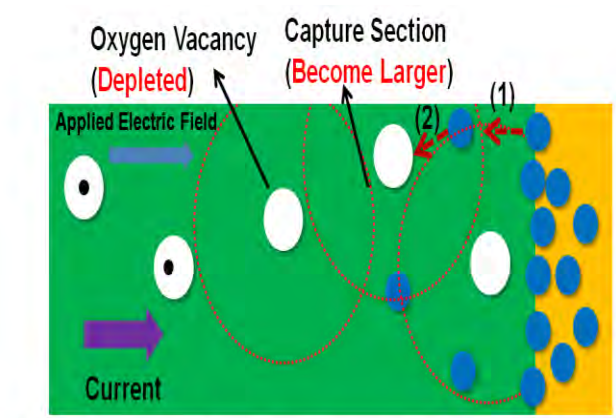
$$V_O^{2+} + O^{2-} \longrightarrow LO$$

4. RESET: Recombination among charged V_0^{2+} and O^{2-}

5. Two essential conditions for RESET

1) **Occurrence of V_0^{2+} states induced by a critical E-field**

2) **Presence of moveable O^{2-}**

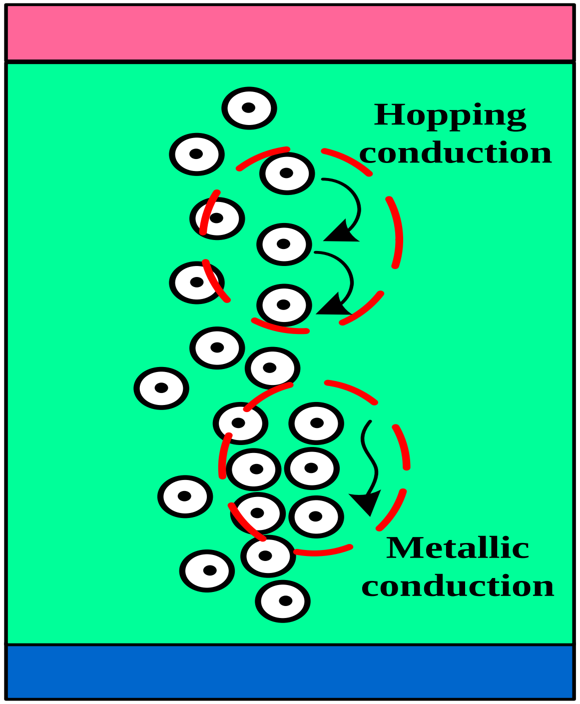


(b) Schematic views for oxygen vacancies with electrons depleted

Formation of the state V_0^{2+} in the filament at a critical E-field

- ✓ **significant capture section**
- ✓ **stable recombination state (LO)**

6. Conduction Properties: due to electron transport along Vo filaments



- Semiconductor-like: V_o are separated from each other
- Metallic-like: V_o are closed each other in the clustered
- First principle calculations support this opinion

Outline

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- Optimization of Synapse
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- The resistive switching characteristics are correlated with geometry of Vo filament
  - generation, recombination, and distributions of Vo
- It is crucial to control Vo distributions and filament geometry to achieve targeted performances

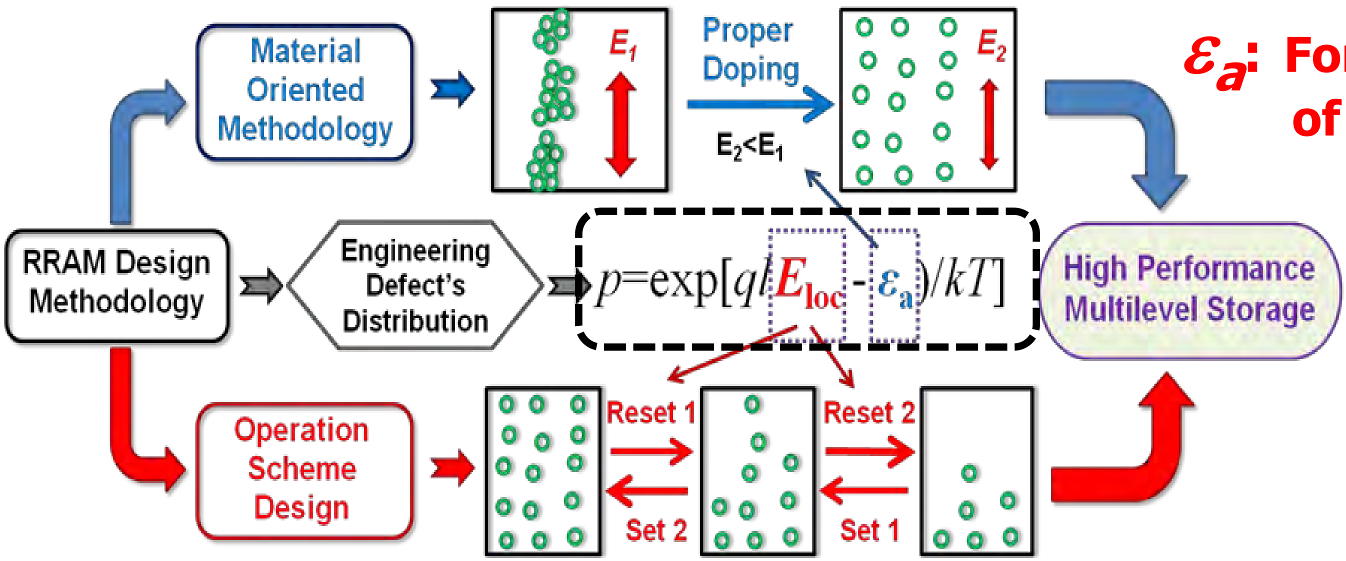
Defect Engineering Approach

- According to crystal defect theory, the generation and recombination probability of Vo is governed by

$$p = exp(\frac{\gamma E_{loc} - \varepsilon_a}{kT})$$

E_{loc}: Local electric field

- A Defect Engineering Approach is proposed [*]



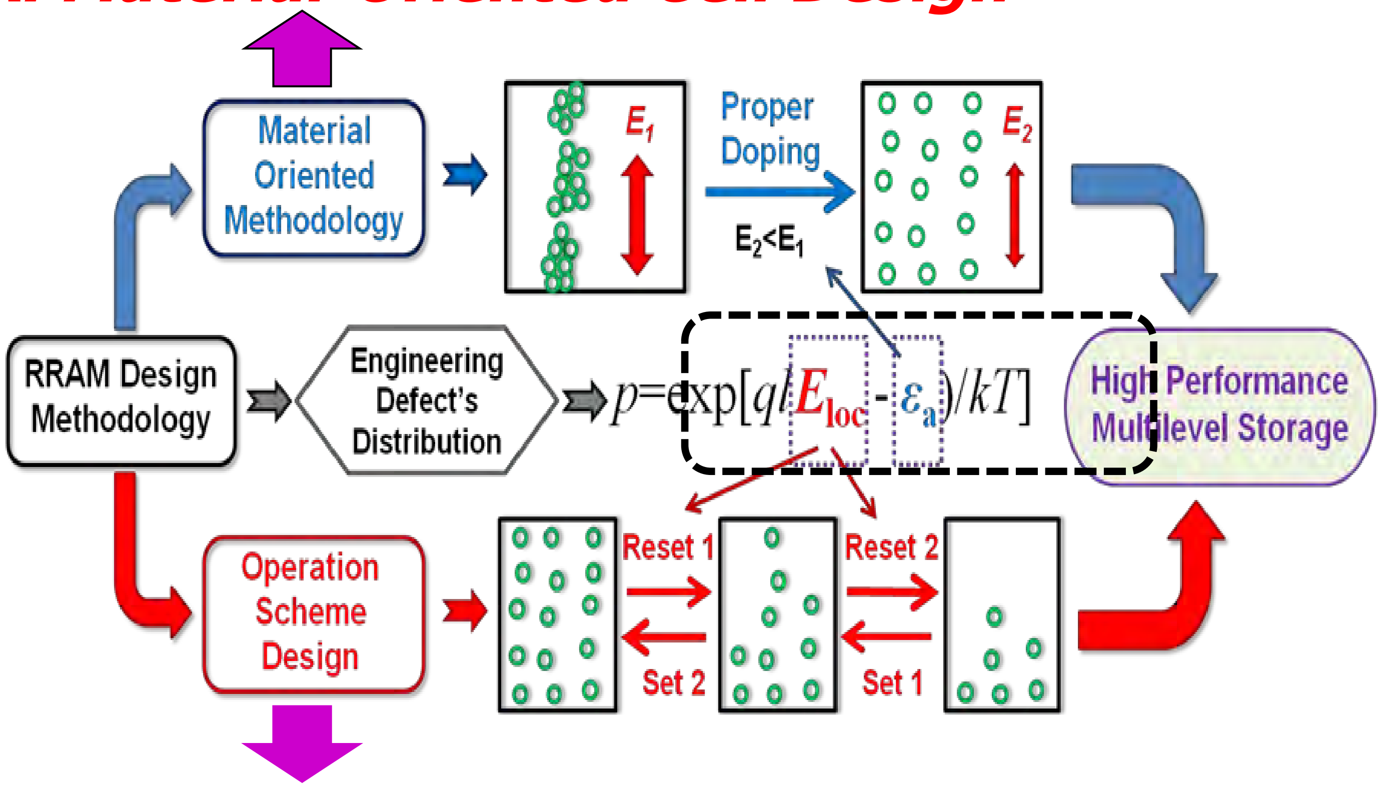
ε_a: Formation energy of Vo

[*] B. Gao et al, IEEE Tran. ED,.Vol 60, p.1379, 2013

□ Defect Engineering Approach

A Defect Engineering Approach is proposed

A. Material-Oriented Cell Design



B. Innovation Operation Scheme

□ Defect Engineering Approach

A. Material-Oriented Cell Design

Calculated formation energy ε_a of V_o [1, 2]

	Undoped (eV)	Ti (eV)	Al (eV)	La (eV)	Ga (eV)
HfO_2	6.53/6.40[a]	6.48	4.09	3.42	–
ZrO_2	6.37/6.09[b]	6.11	3.66	3.74	3.77

a) A. S. Foster et al. PRB 65, 174117(2002) ; b) A. S. Foster et al. PRB 64, 224108(2001) ; c) T. R. Paudel et al. PRB 77, 205202(2008)

Trivalent La or Al doping could effectively reduce ε_a

[1] H.W. Zhang et al, APL 96, 2010 [2] B. Gao et al, VLSI2009

Defect Engineering Approach

A. Material-Oriented Cell Design

- **In the resistive switching (RS) layers of Al- or La-doped HfO_2 or ZrO_2 [1-2]**
  - **V_o are preferentially generated near the trivalent Al or La sites**
  - **Filaments are preferentially formed along the dopant sites**
  - **Better controllability of resistive switching could be achieved by using proper doping approaches**

[1] H.W. Zhang et al, APL 96, 2010 [2] B. Gao et al, VLSI2009

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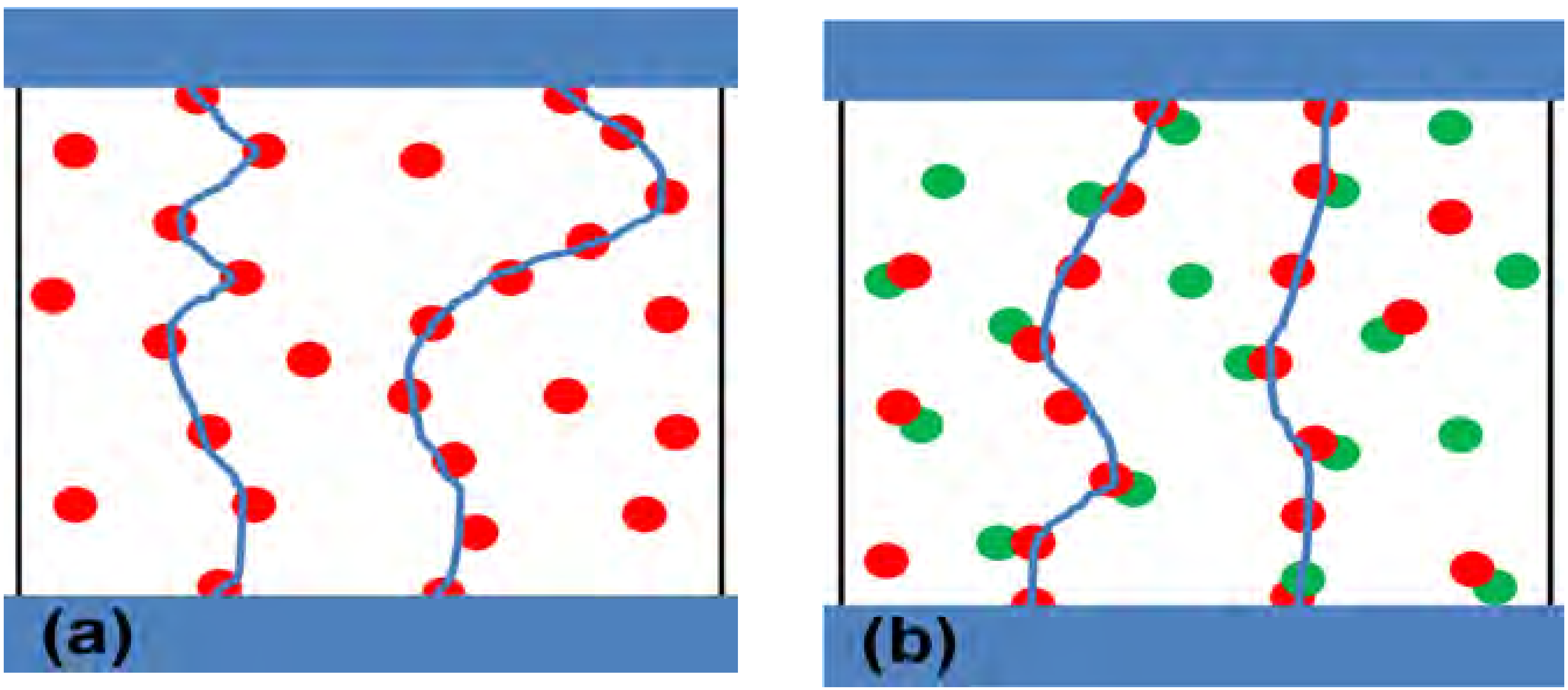
□ Defect Engineering Approach

A. Material-Oriented Cell Design: Doping Effect

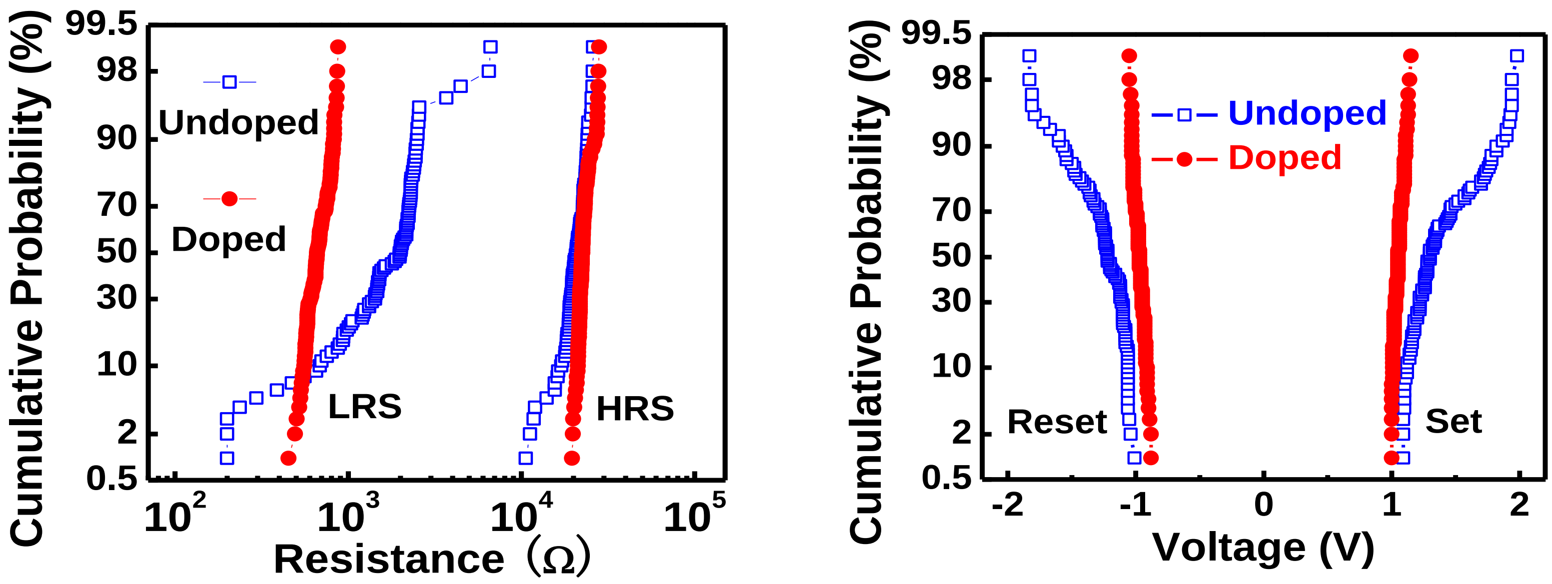


Vo distributions and CFs are full-randomly

Vo and CFs are formed near the dopant sites

☐ Defect Engineering Approach

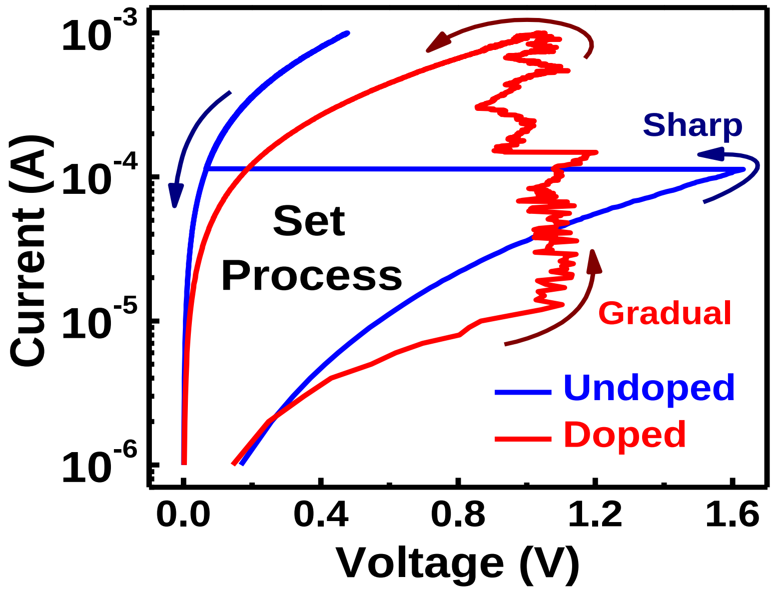
Improved Uniformity by proper doping

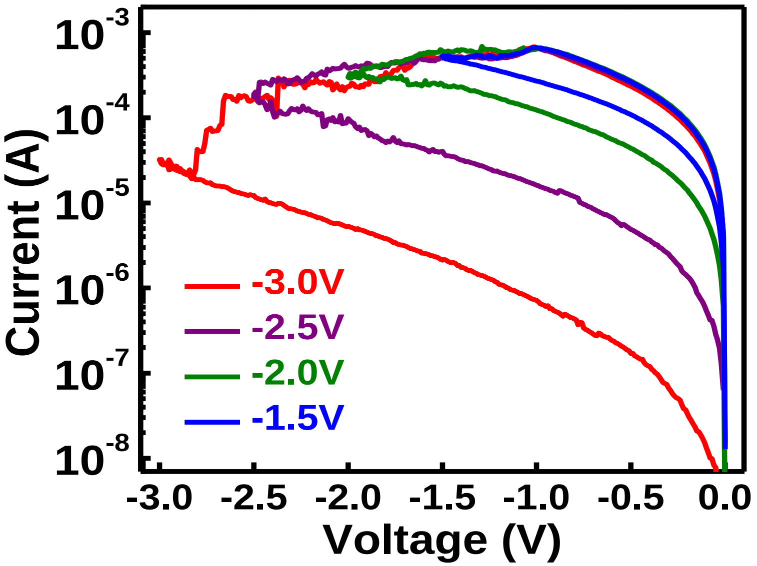


Expected uniformity improvement is identified by experiments

◻ Defect Engineering Approach

Gradual transitions both in SET and RESET



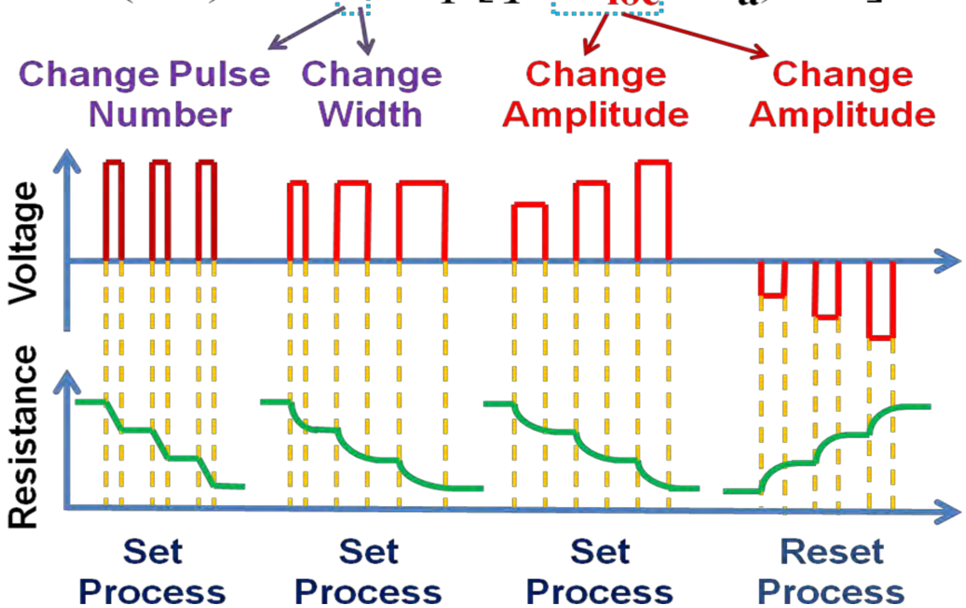


- **Better controllability on RS processes achieved in doped HfOx devices**
- **This is beneficial for RRAM as a synapse**

□ Defect Engineering Approach

B. Innovation Operation Scheme

$$N(Vo) = v\, t\, \exp[ql(E_{loc} - \varepsilon_a)/kT]$$

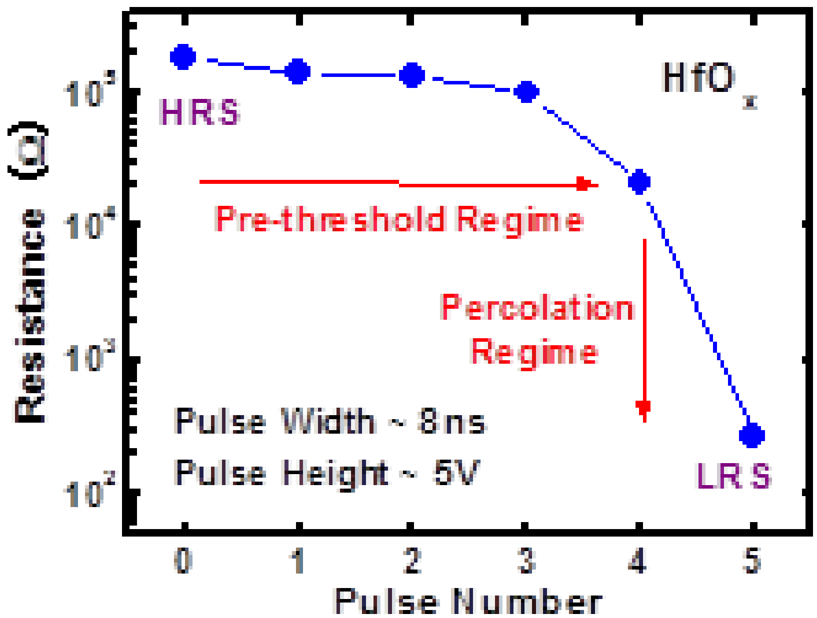


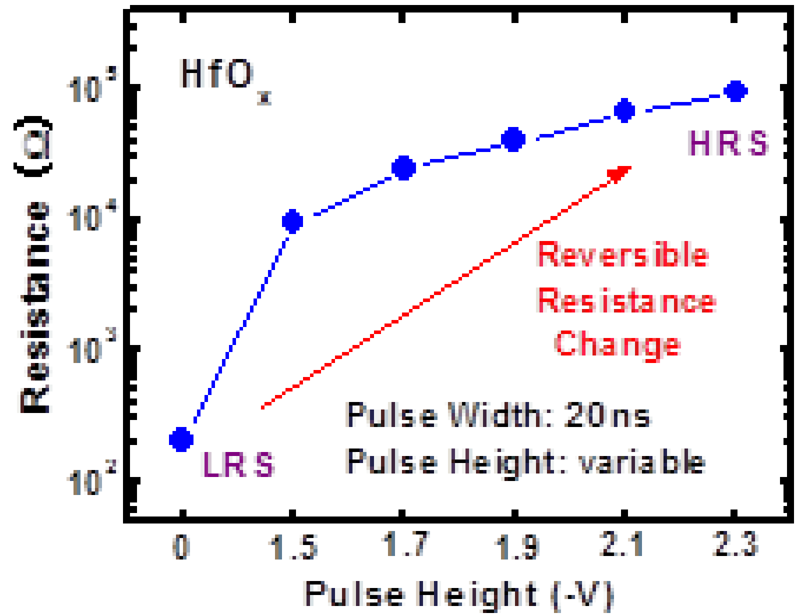
- Vo density is dependent on local electric field and switching time
- Operation schemes (switching time and local electric field) can be used to control Vo distributions

Different operation schemes can be expected to achieve different response characteristics!!

□ Defect Engineering Approach

B. Innovation Operation Scheme

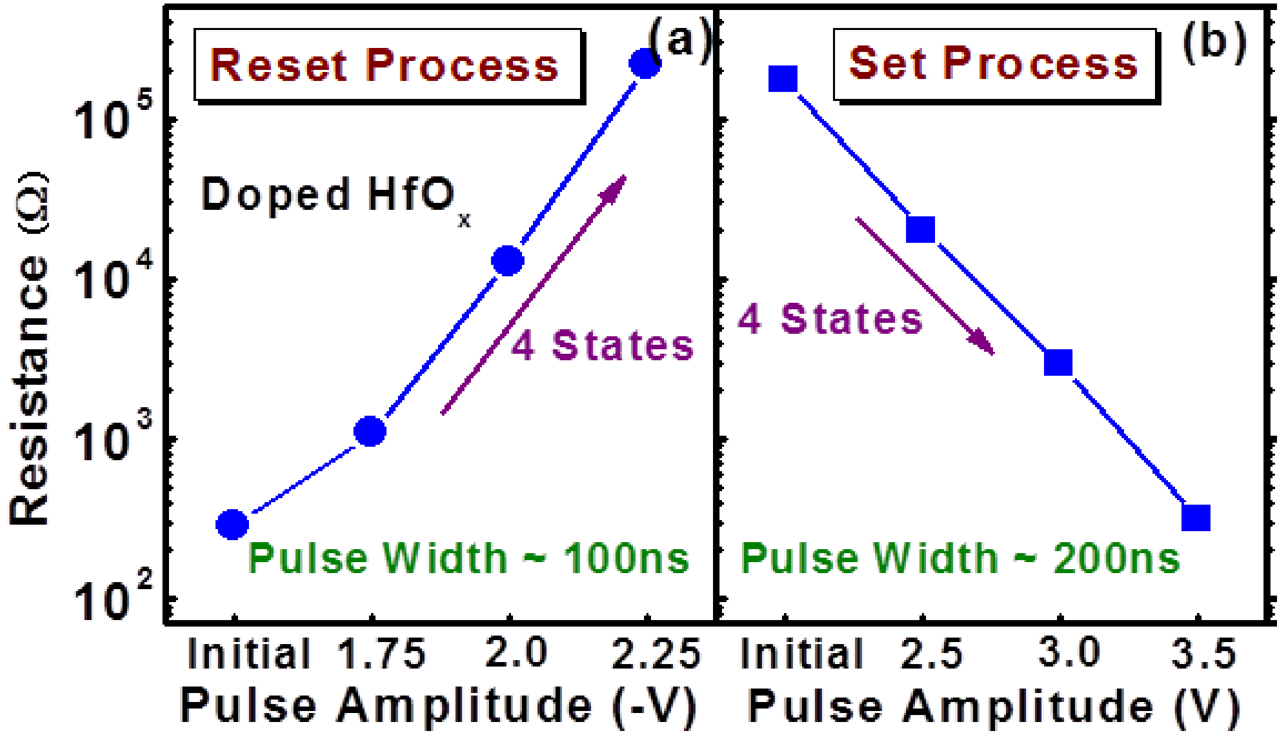




Non linear resistance change as a function of pulses is observed when short pulses are applied.

□ Defect Engineering Approach

B. Innovation operation scheme



Nearly linear resistance change with pulses is realized when wider pulses are applied.

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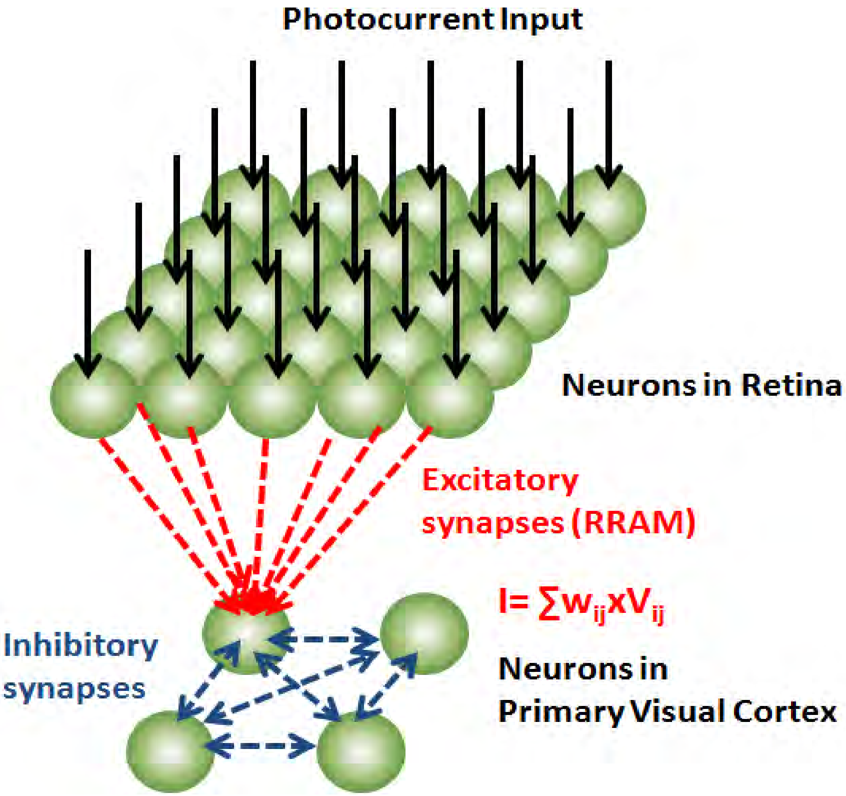
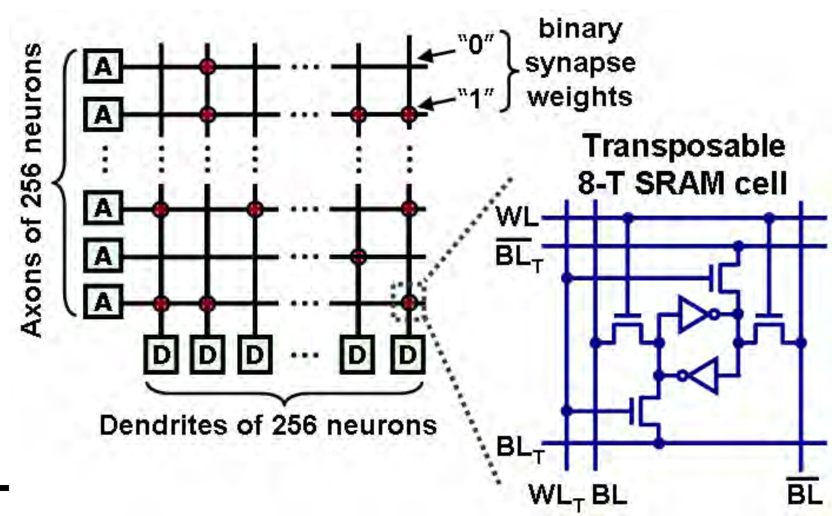
- **Optimization of Synapse**
- **Summary**

TMO-based Synaptic Devices

❑ Neuromorphic Visual Systems



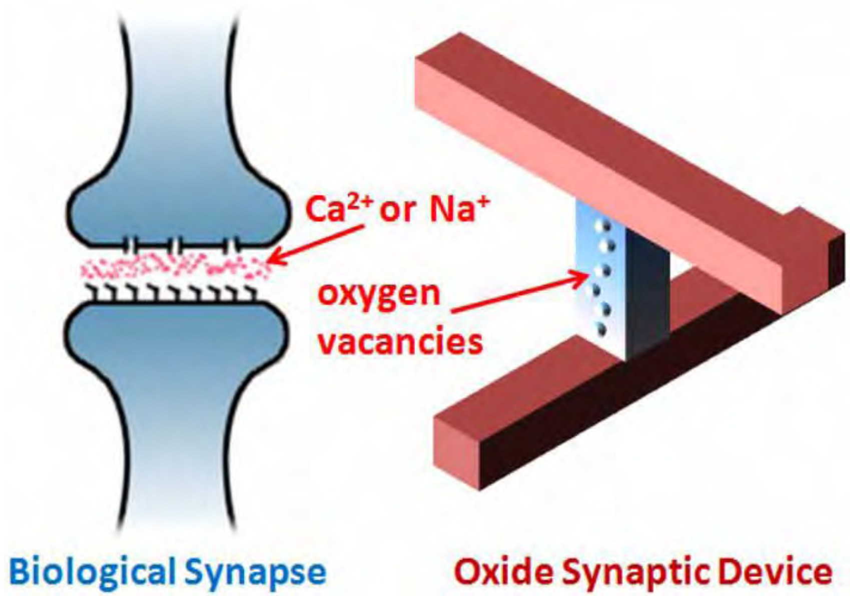
- **A great amounts of synapses are needed**
- **A typical CMOS-based binary synapse consisted of a 8T-SRAM cell [*]**
- **New synapse is needed**



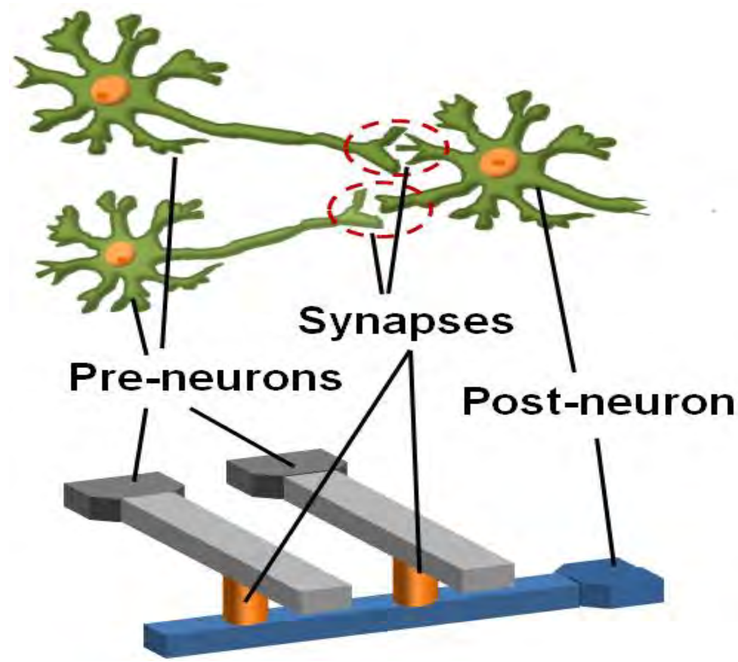
[*] SRAM based CMOS hardware (IBM, CICC 2011)

TMO-based Synaptic Devices

□ TMO-RRAM-based synapse is promising



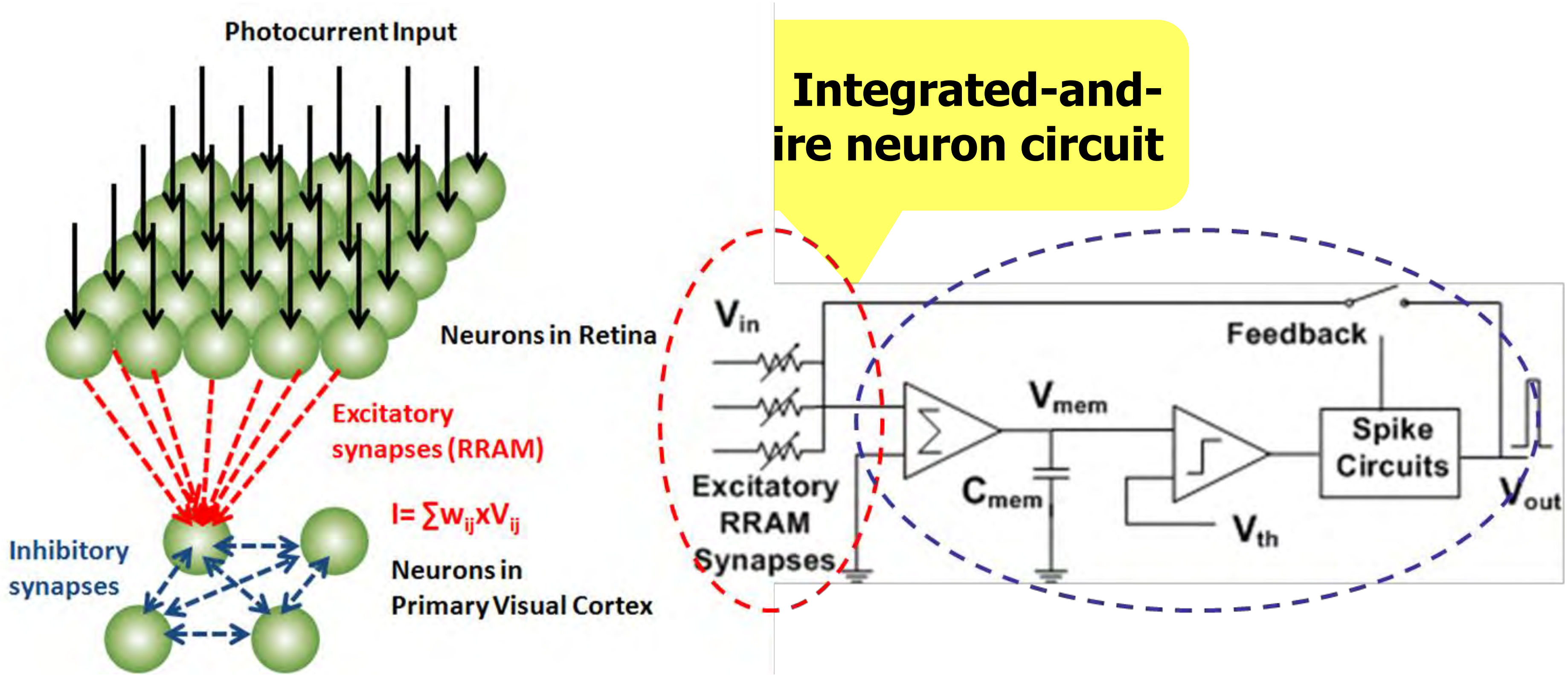
Analogy between biological and artificial RRAM synapse.



Analogy between biological and RRAM based neural networks.

Optimization of Synapse

Artificial Visual System-based on RRAM and Winner-Take-All algorithm is constructed

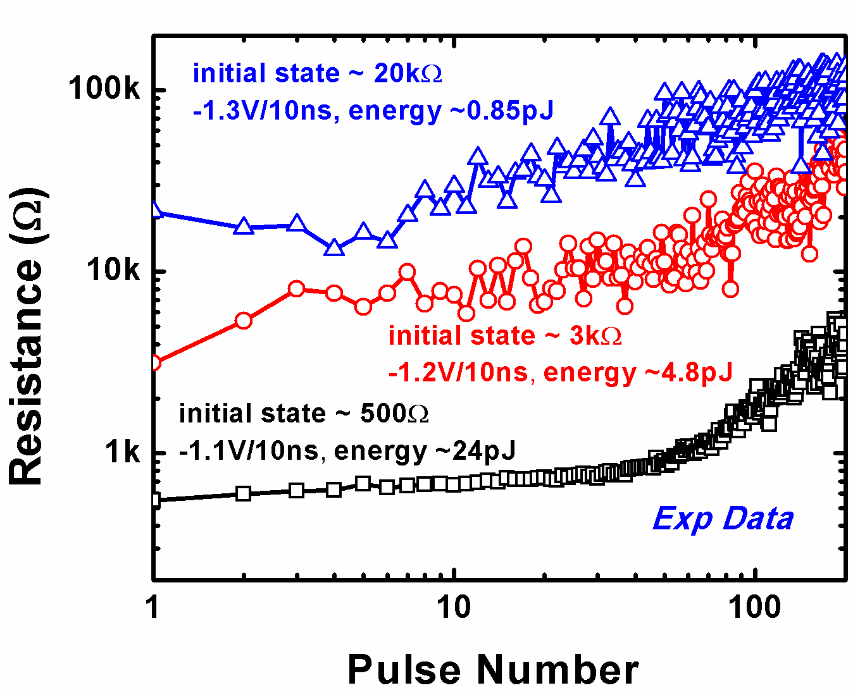


1st layer: 32×32 neurons; 2nd layer: 4×4 neurons
between 1st layer and 2nd layer: 16348 RRAM synapses

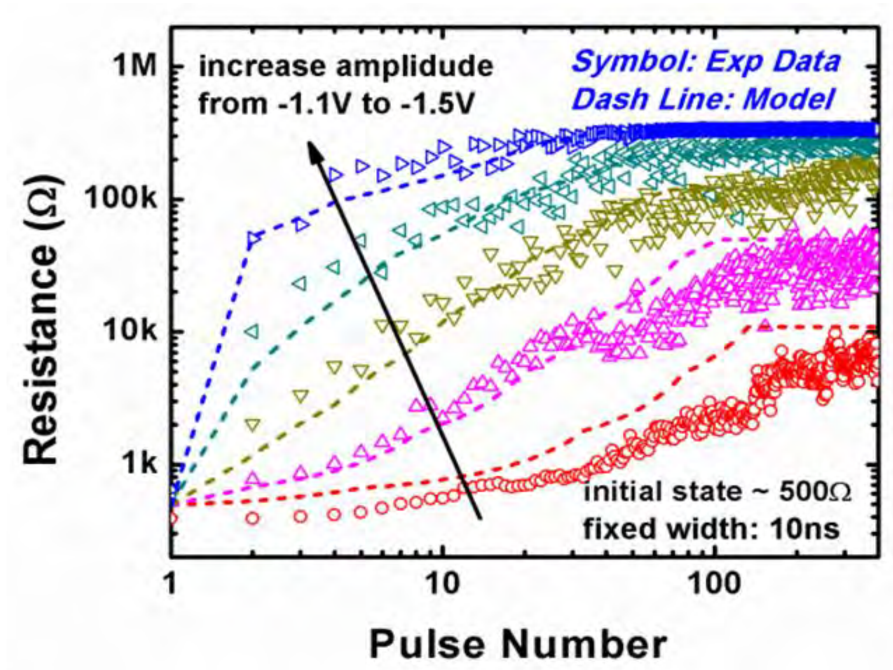
Synaptic Device Behavior

Multi-level resistance states and ultra-low spike energy <1pJ are demonstrated [#]

[#] S. Yu, et al, IEDM2012, p.239



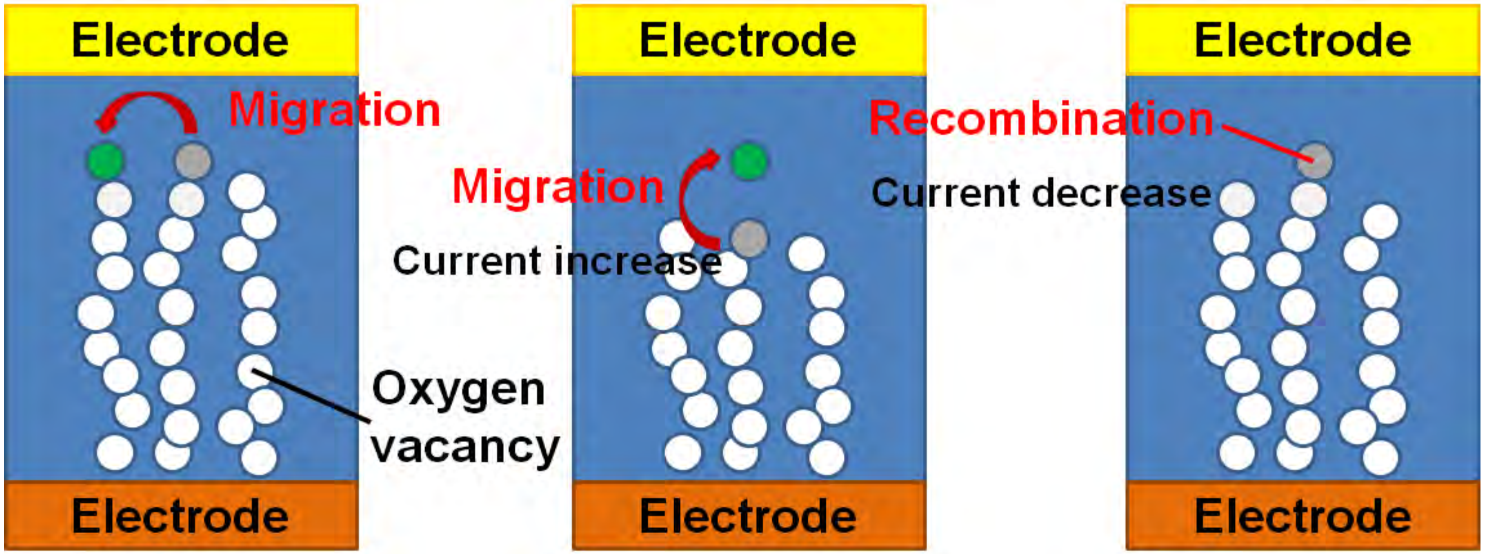
Dependence of energy/spike on initial R for training process



Measured and fitted training process with pulse amplitudes.

Model of TMO-based Synapse

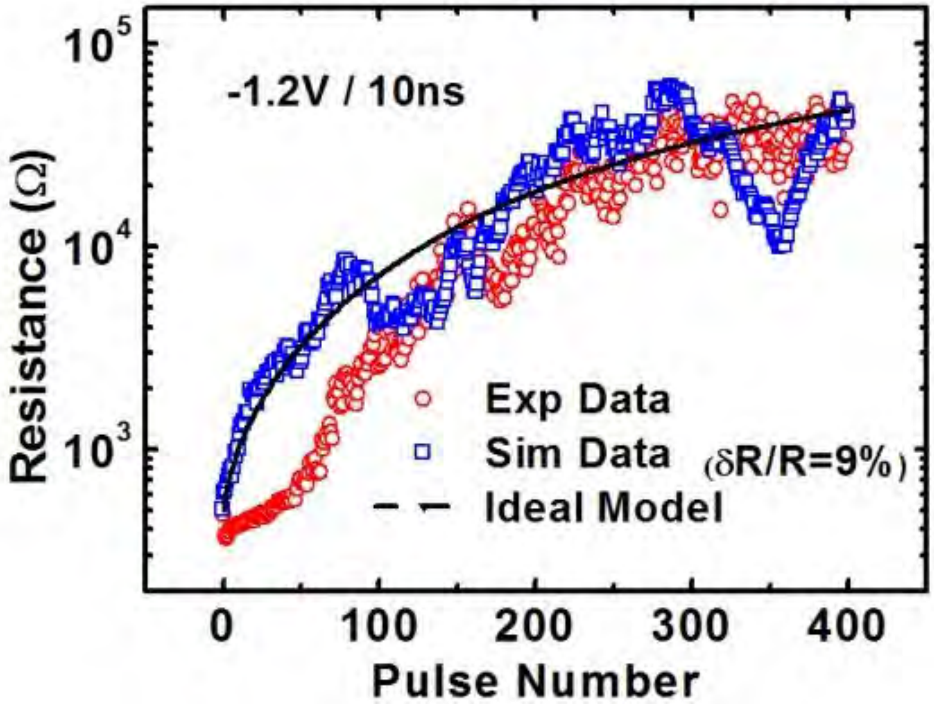
A model is developed for the training process of TMO-RRAM synapse



- Resistance variation effect during training process
- Model parameters can extracted from measured data.

TMO-based Synaptic Devices

Resistance Evolution under 400 RESET pulses

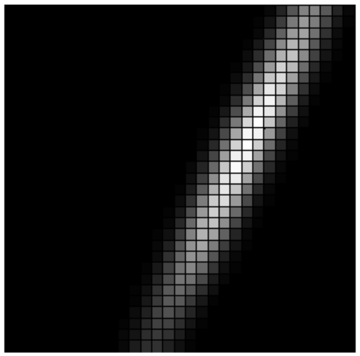


- In low resistance regime, fluctuation is smaller but suffers from high spike energy
- In high resistance regime, low spike energy but larger fluctuation presented

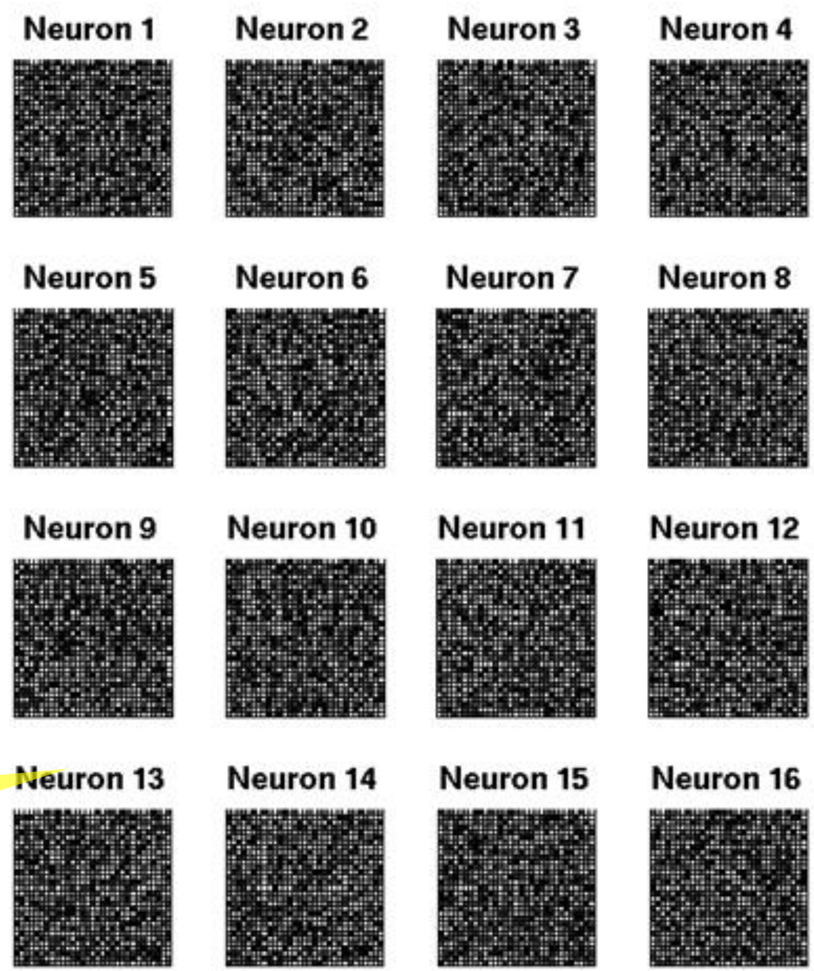
Larger fluctuation or variation may cause degradation of recognition accuracy of the neuromorphic systems

Simulated System Performances

Training Images and Initial Conductance Map



**2D Gaussian bar:
Random center and
random orientation**

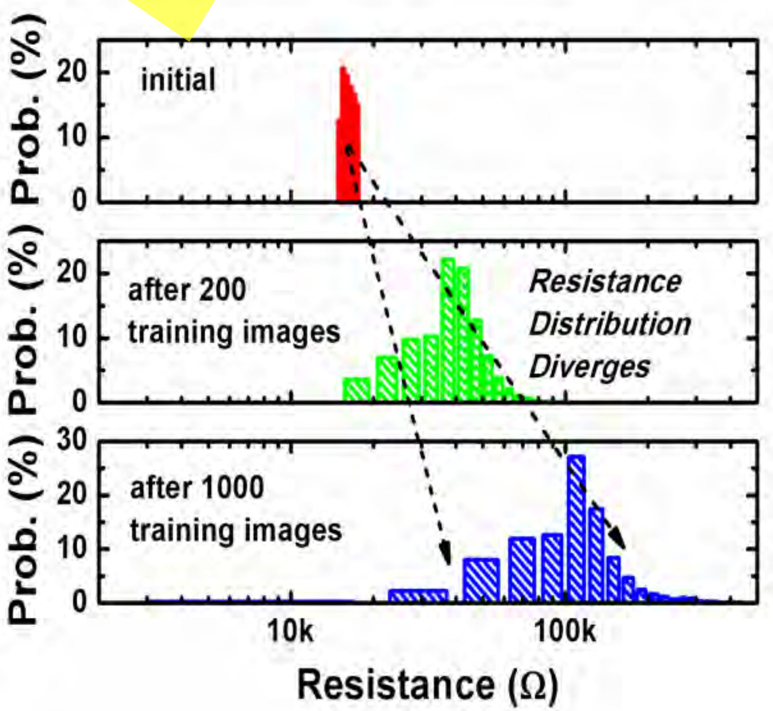


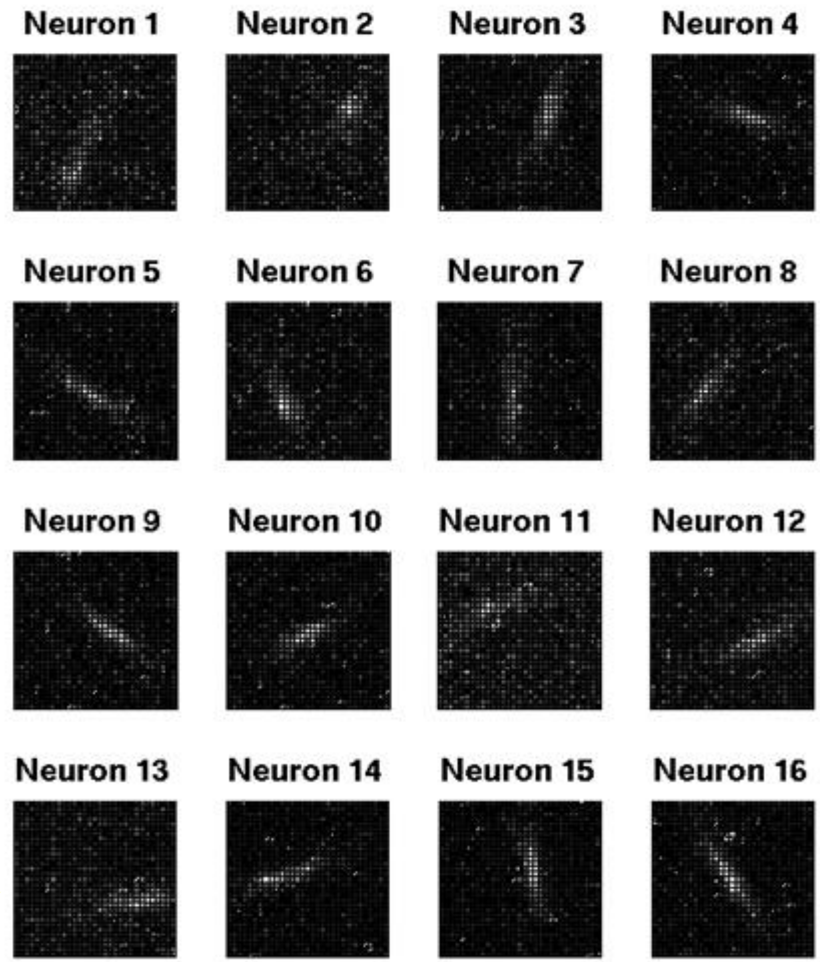
**Before the training
randomized around 20kΩ**

Simulated System Performances

Resistance Diverges and Orientation Map Emerges

During the training

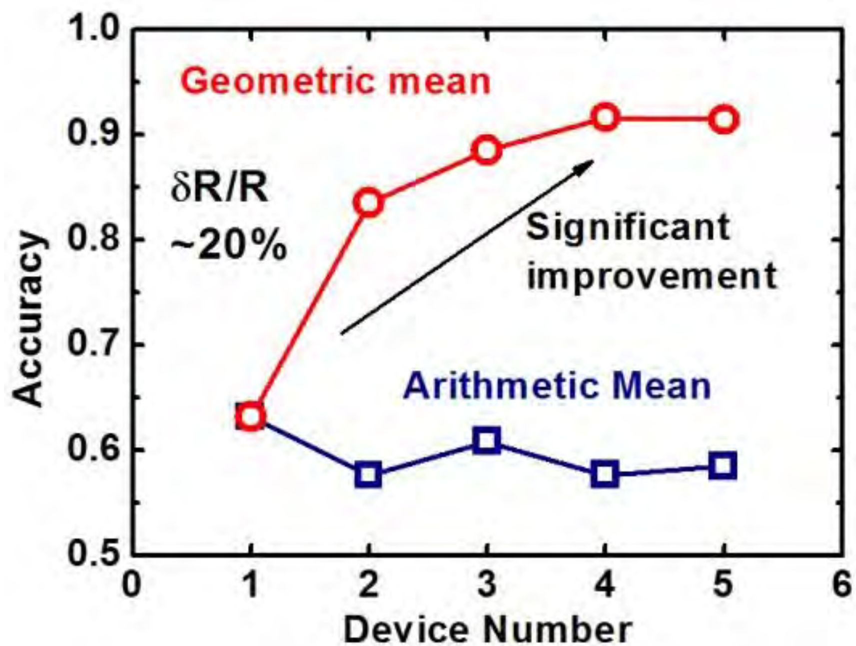




After the training

Optimized Synaptic Devices

Can we realize synaptic performances with both low spike energy and high recognition accuracy ? ?

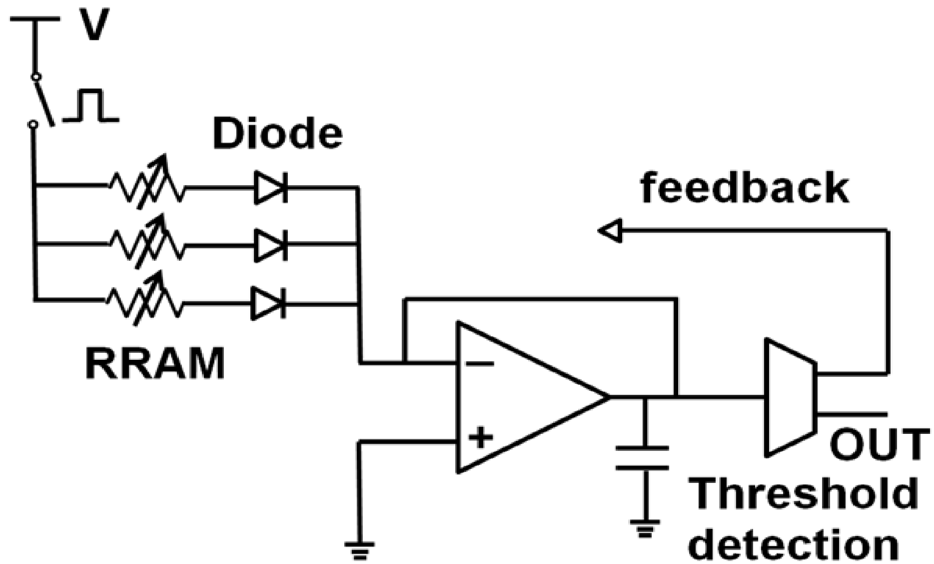


Geometric mean of more than 2 devices in parallel can significantly suppress the impact of intrinsic fluctuation effect

Optimized Synaptic Devices

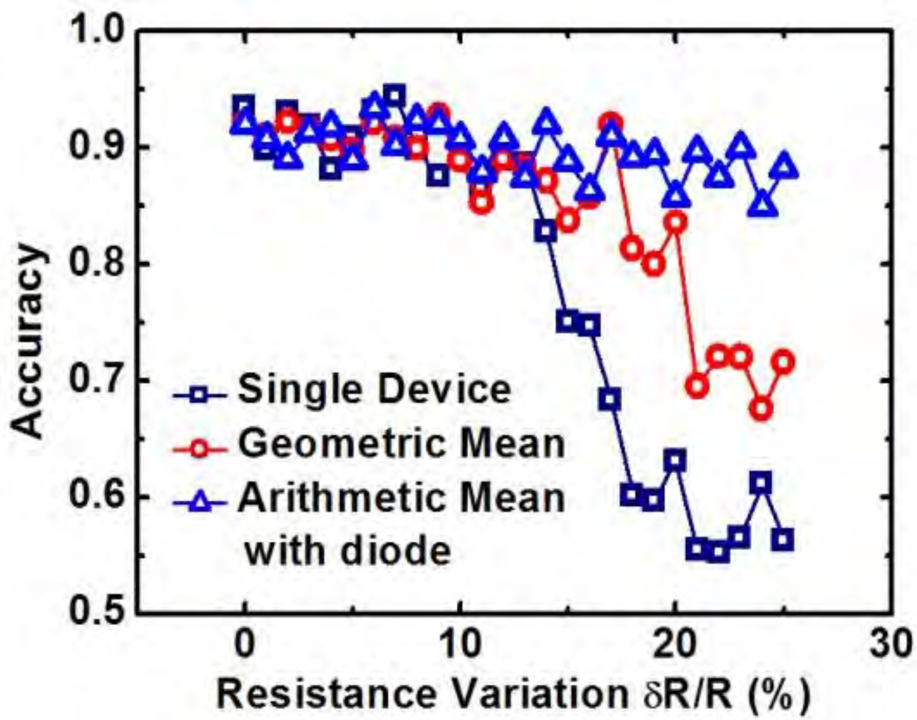
Optimized architecture of a neuromorphic system using robust synapse is proposed

- A 1D1R synaptic cell is introduced
- 1D is applied to perform logarithm function on the device resistance



Geometric mean calculation on resistance is replaced by the logarithm function.

Simulated System Accuracy

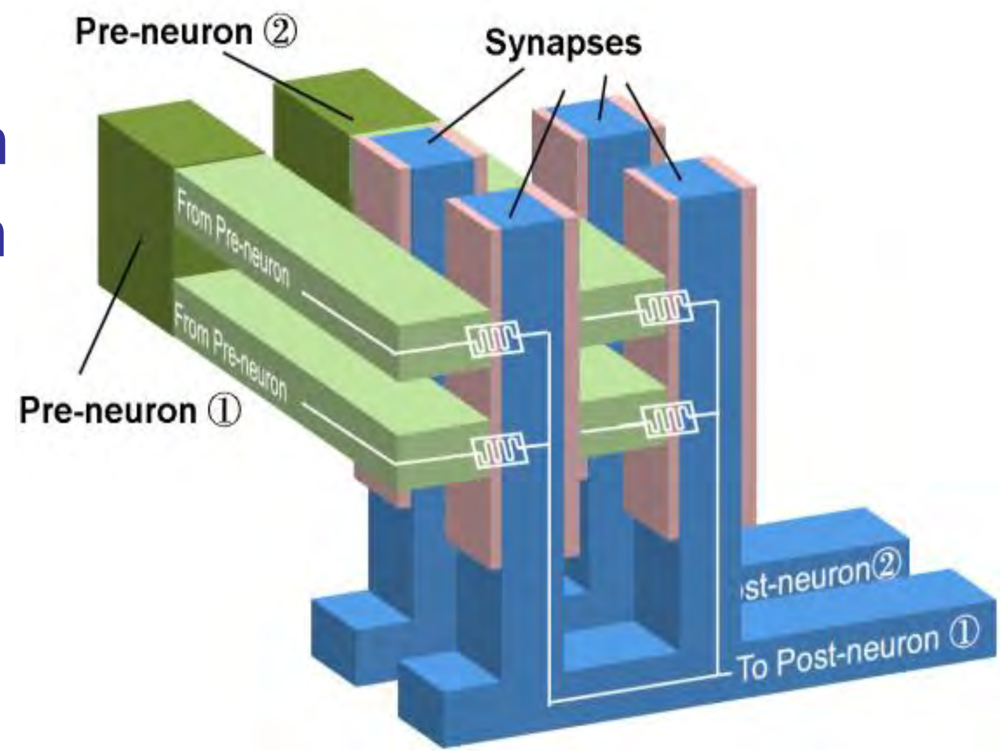


- **Single RRAM device**
- **Geometric mean of two devices**
- **Two parallel 1D-1R cells**

- **Significant improvement on recognition accuracy is achieved by the architecture of 2 parallel 1D1R.**
- **Array integration approach is a great challenge**

Optimized Synaptic Devices

- 3D vertical ReRAM array architecture as synapses
  - Easily to achieve high density of integration
  - Significantly to immunize resistance variation during training process of synapses



A synapse: devices in the same pillar electrode

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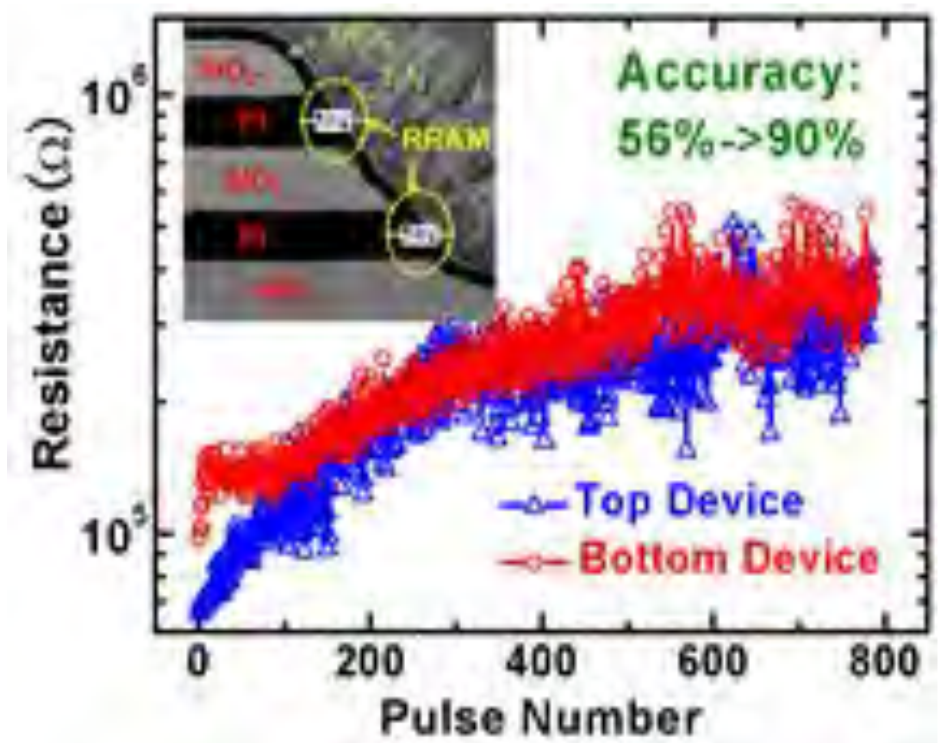
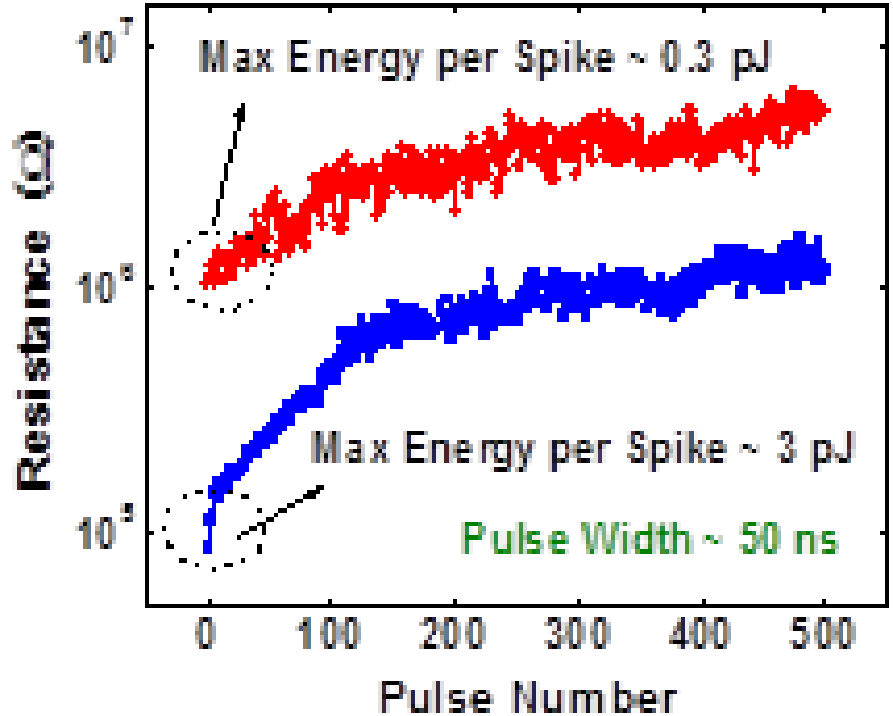
3D Vertical RRAM Arrays

- **Measured training process of top and bottom ReRAM devices in the 3D vertical array**
  - **2 layered devices are fabricated**
  - **Nearly constant device performance both in top and bottom layers is measured.**
  - **Significantly improved accuracy achieved.**



TMO-based Synaptic Devices

- Measured training process for the 3D vertical synaptic devices
  - Different initial R states can be achieved by different current compliances
  - Initial R is set to ~1MΩ, maximum energy consumption per spike <1 pJ.



B. Gao et al, ACS Nano 8, 6998, 2014

Outline

- Introduction
- Physical Mechanism
- Defect Engineering Approach
- Optimization of Synapse
- **Summary**

Summary

- A unified physical mechanism is proposed to elucidate the resistive switching of TMO-RRAM
- A defect engineering approach is developed to design and optimize RRAM performances
- Excellent controllability on RS behaviors is demonstrated in optimized RRAM devices based on the defect engineering approach.

Summary

- **Multi-level resistance states are realized in the optimized RRAM**
- **Robust synaptic behaviors with sub-pJ energy per spike are realized in the optimized RRAM**
- **Optimized architectures of TMO-RRAM synapse are proposed to improve system performances.**