A Two-Step Set Operation for Highly Uniform Resistive Switching ReRAM by Controllable Filament

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Outline

- Introduction & Motivation
- Two-step set operation ReRAM
  - Experimental
  - Electrical Characterization
  - Improved Switching uniformity
- Gradual set operation ReRAM
  - Motivation/Experimental
  - Electrical Characterization
  - Improved Switching Uniformity
- Conclusion

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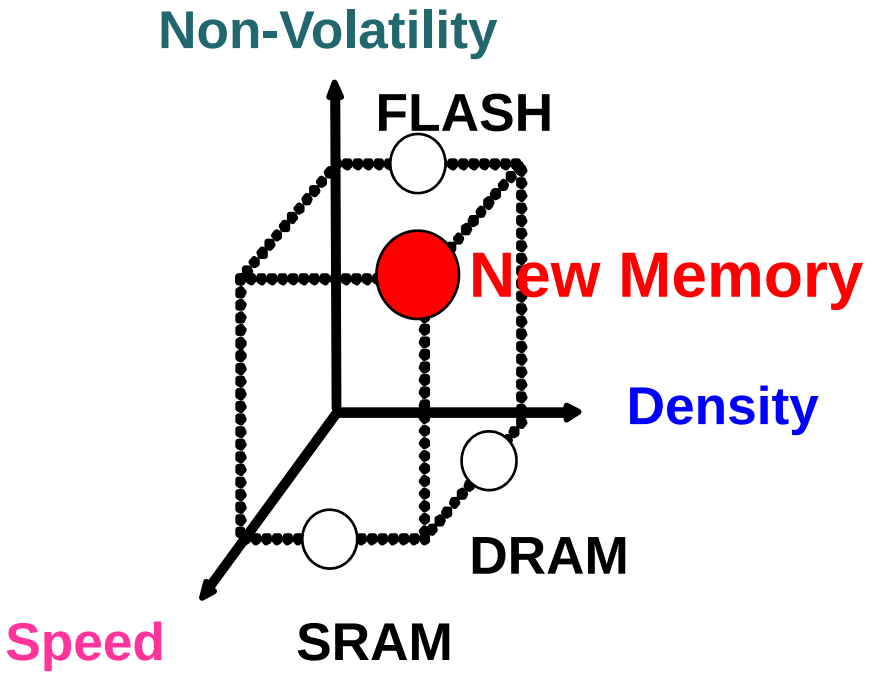
Introduction

- **Motivation**
  - **Scaling limit of charge based memory**
  - **ReRAM is the most possible candidate**



ITRS ROAD MAP 2010

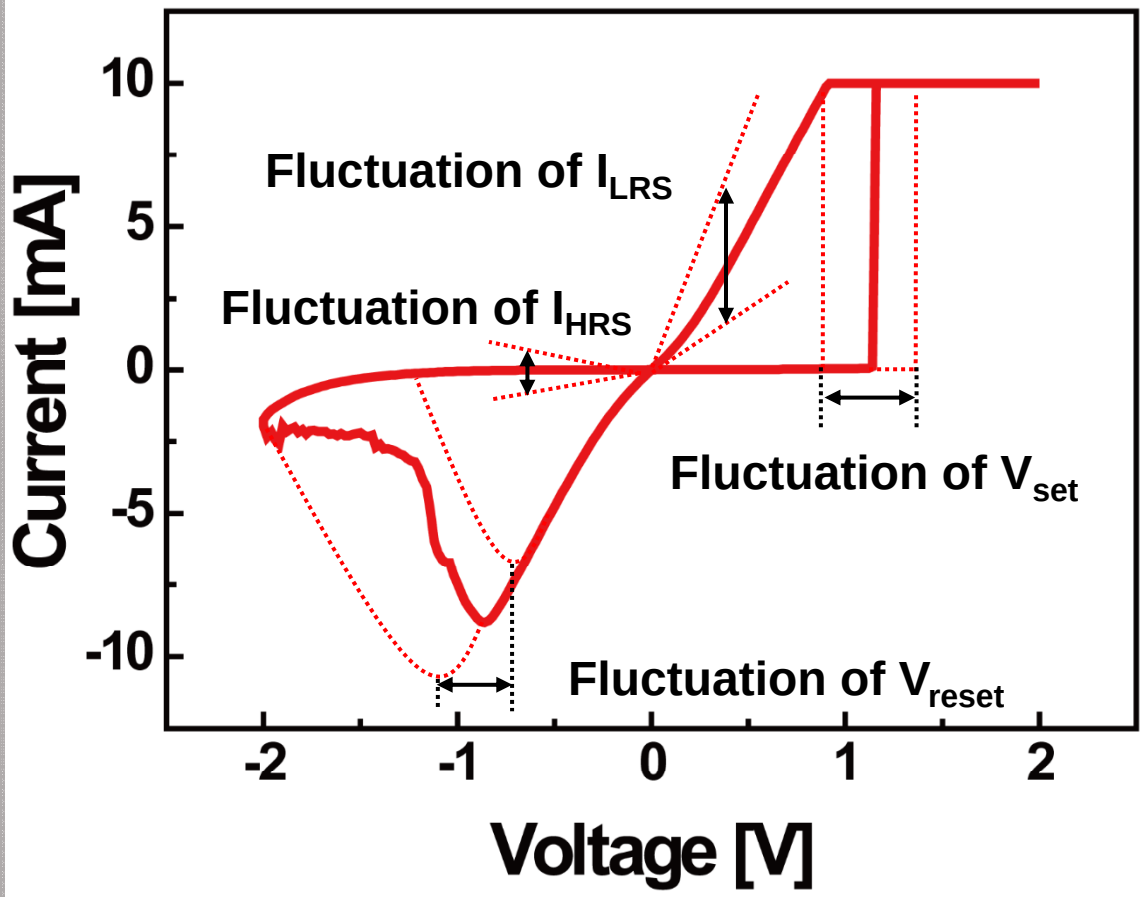
✓ **Filamentary ReRAM**

1. Advantages
- **Fast operation**
- **High scalability**

2. Disadvantages
- **Variability**
- **Retention**

Introduction

- **Motivation**
  - Variability of Resistive Switching Parameters



Large distribution of switching parameters

↓

Unstable resistive switching operation

↓

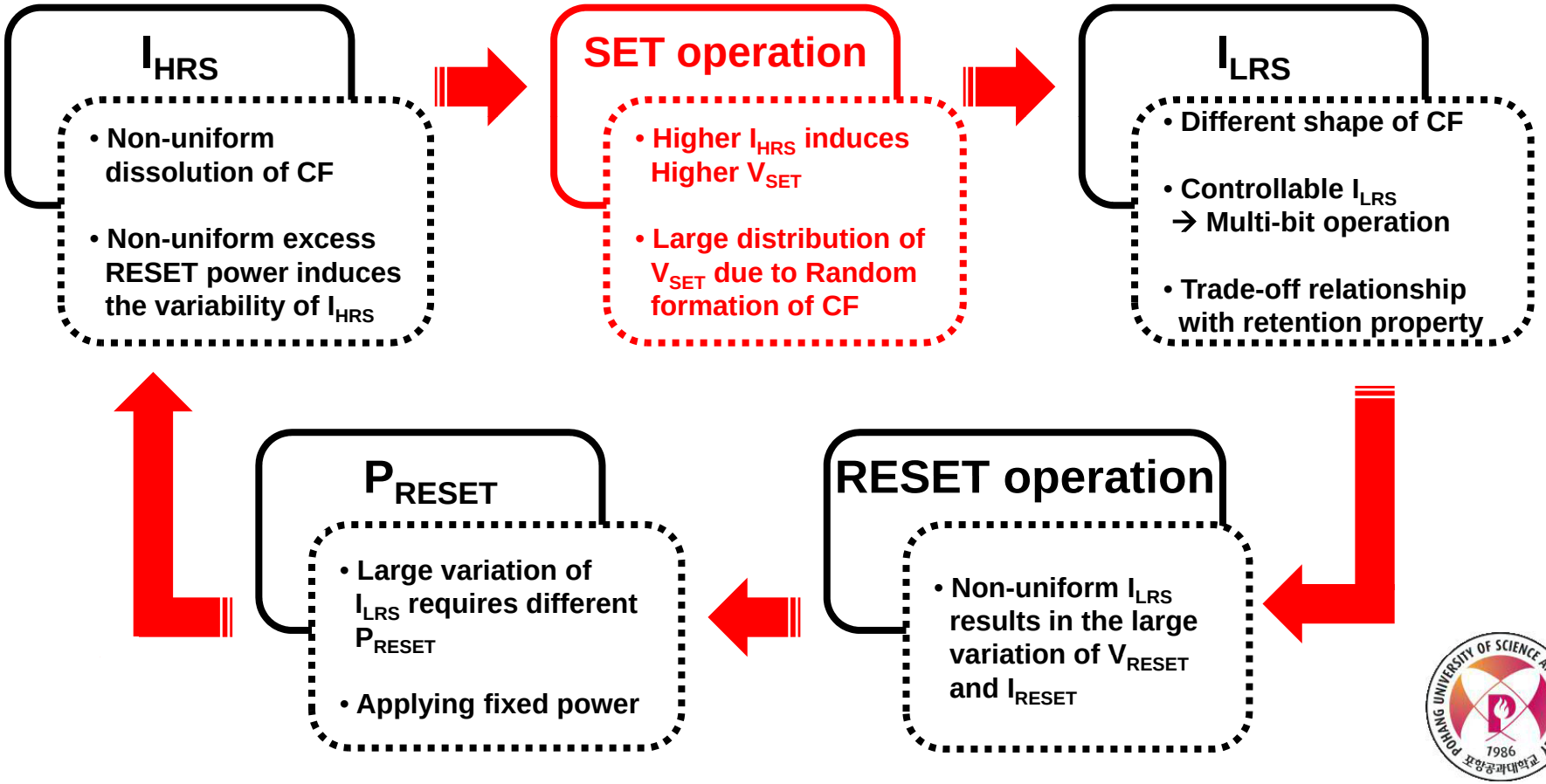
Fundamental understanding of switching parameter variability

↓

Relationship between each parameter

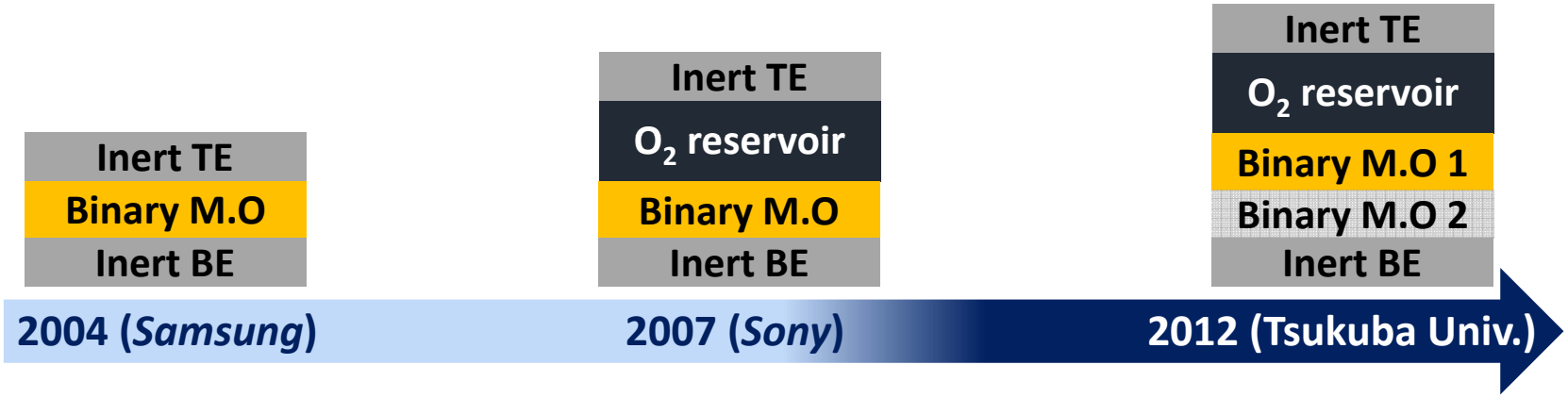
Introduction

- **Motivation**
  - Chain Relationship for Variability Degradation



Introduction

- **Motivation**
  - Stack (layer) engineering for reliability



(I. G. Baek et al., IEDM 2004) *(K. Aratani et al., IEDM 2007)* *(K. Kamiya et al., IEDM 2012)*

✓ Larger μ_o
=> Difficult filament dissultion in M.O

✓ μ_O fine-tuning for stable on/off states

(K. Kamiya et al., IEDM 2012)
(L. Goux et al., VLSI 2013)

Outline

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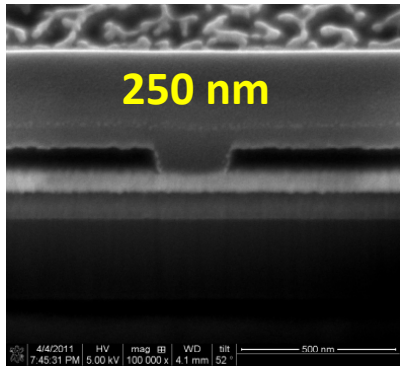
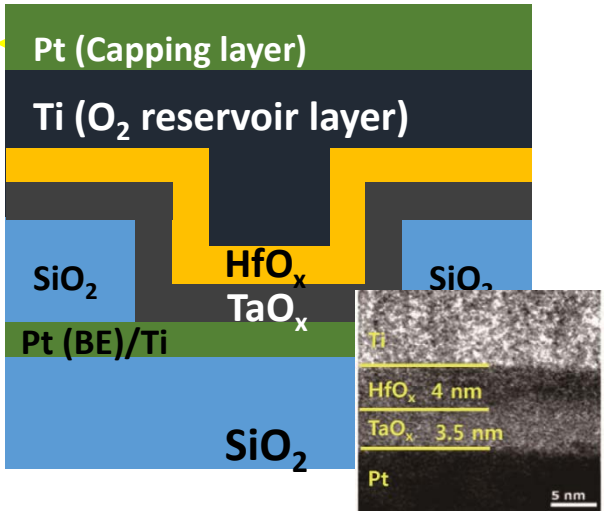
- **Two-step set operation ReRAM**
  - **Experimental**
  - **Electrical Characterization**
  - **Improved Switching uniformity**
- Gradual set operation ReRAM
  - Motivation/Experimental
  - Electrical Characterization
  - Improved Switching Uniformity
- Conclusion

Triple-layer ReRAM of Two Oxides

1. Experimental on 250 nm via-hole pattern substrate

- SiO_2 deposition by PECVD
- Pt BE deposition by sputter
- SiO_2 deposition by PECVD & 250 nm Patterning
- TaO_x (3.5 nm) deposition in Ar & O_2 ambient by RF sputtering
- HfO_x (4 nm) deposition by ALD
- Ti oxygen reservoir layer and Pt
- **Ti/HfO_x/TaO_x/Pt ReRAM**

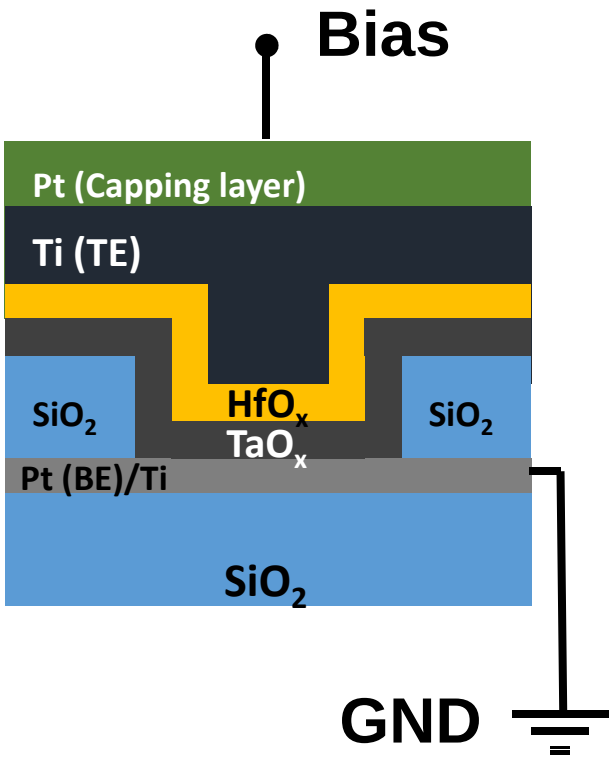


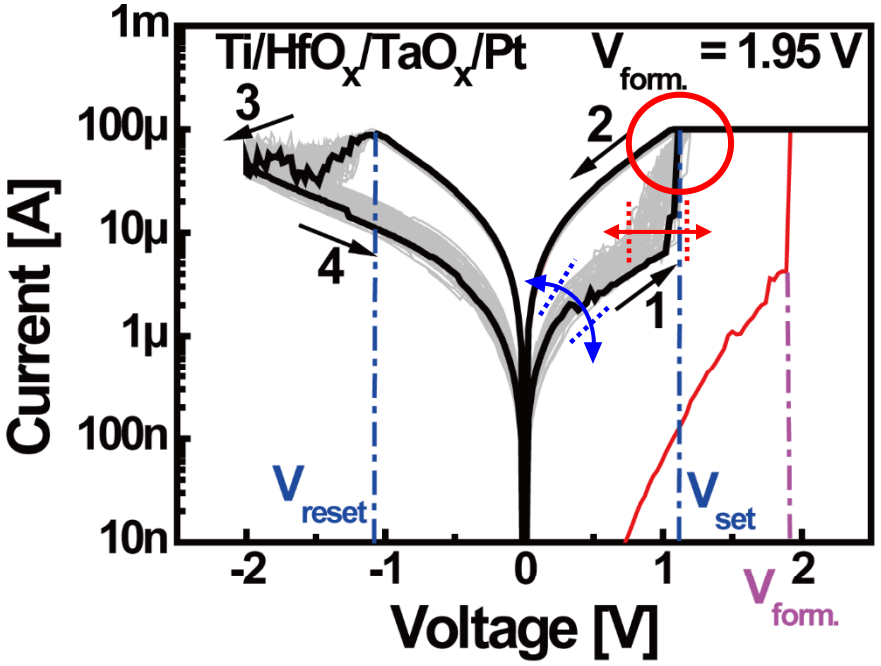


Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- DC bias



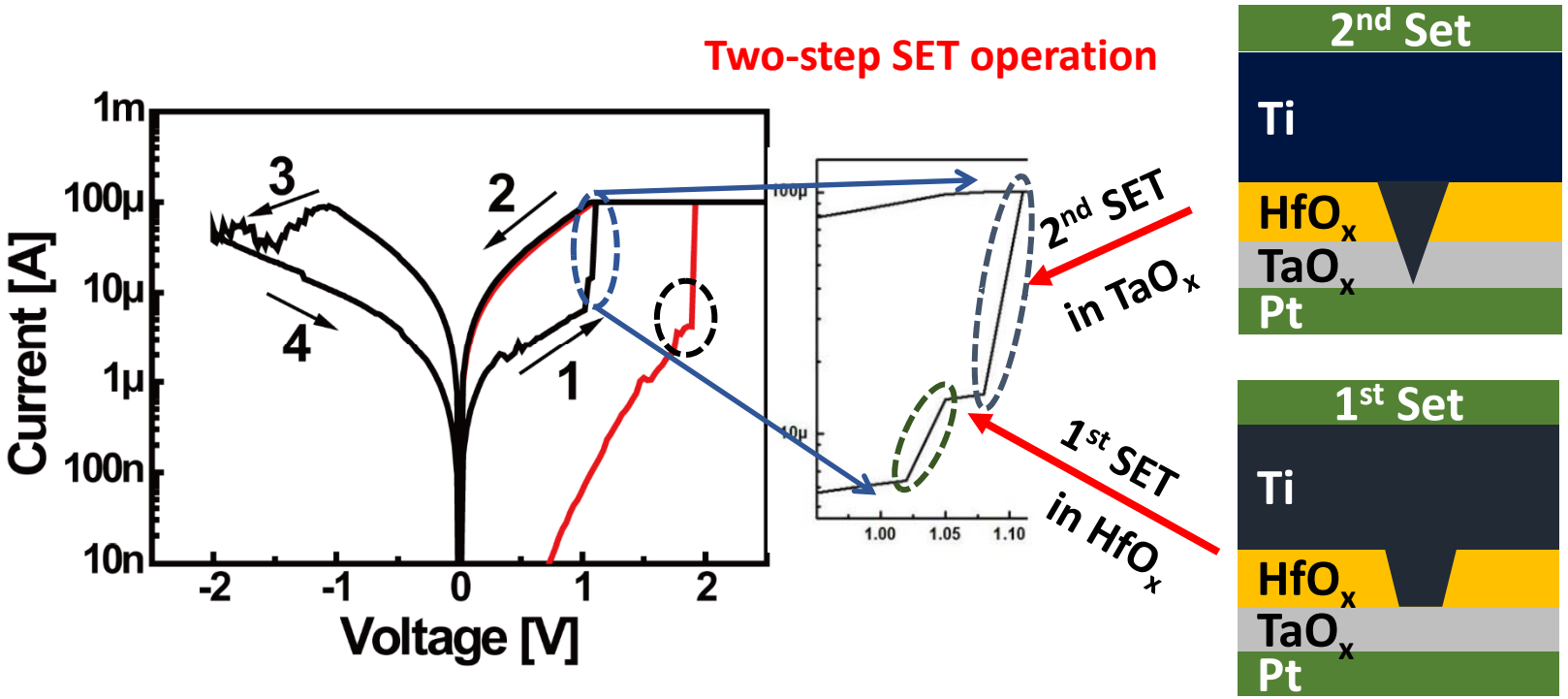


✓ Uniform set operation ➡ ✓ Uniform LRS distribution

Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- Two-step set operation

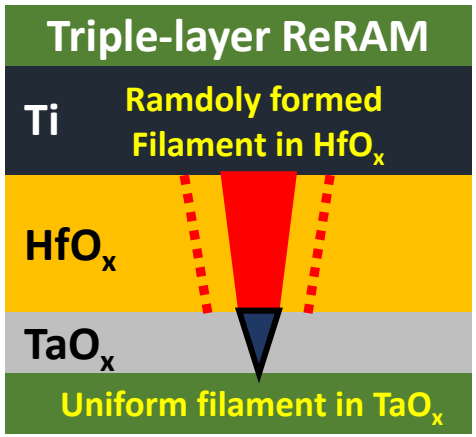


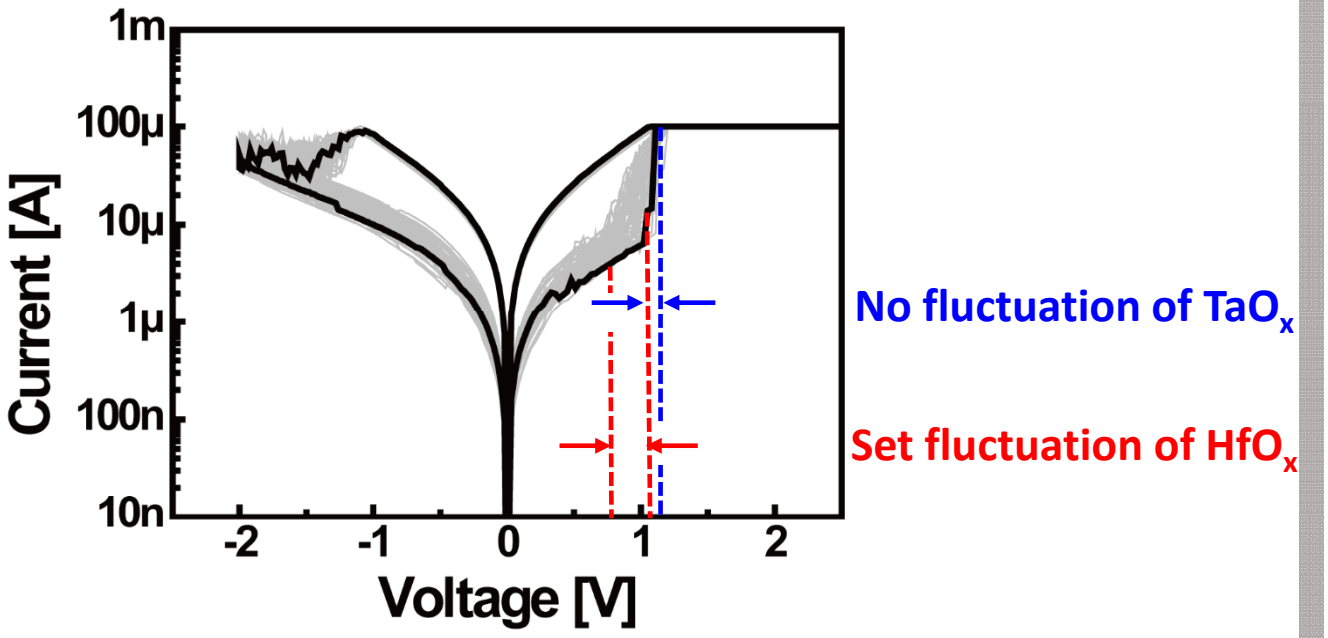
✓ Critical power is required to be set state of TaO_x

Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- Different filament formation ability in metal oxides



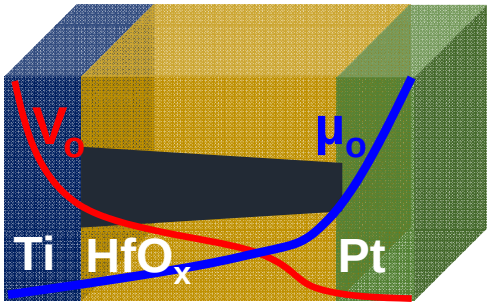


✓ Variability in HfO_x, but TaO_x requires critical set power

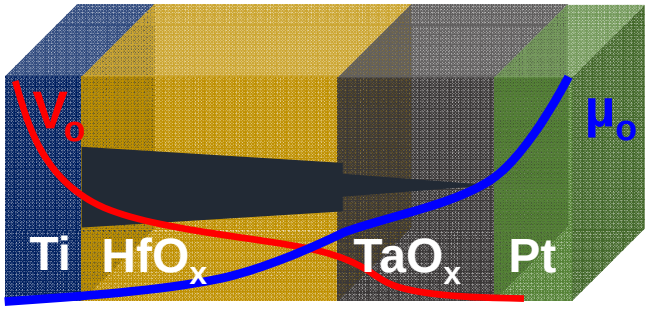
Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- Defect distribution



◆ Bi-layer ReRAM



◆ Triple-layer ReRAM

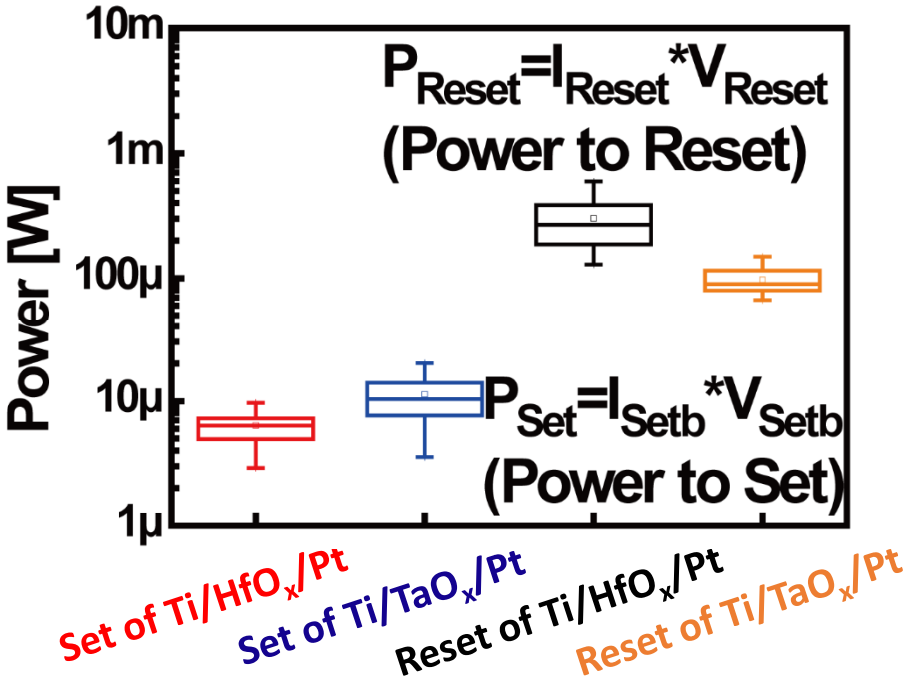
✓ Different filament formation ability with different chemical potential (μ_o)

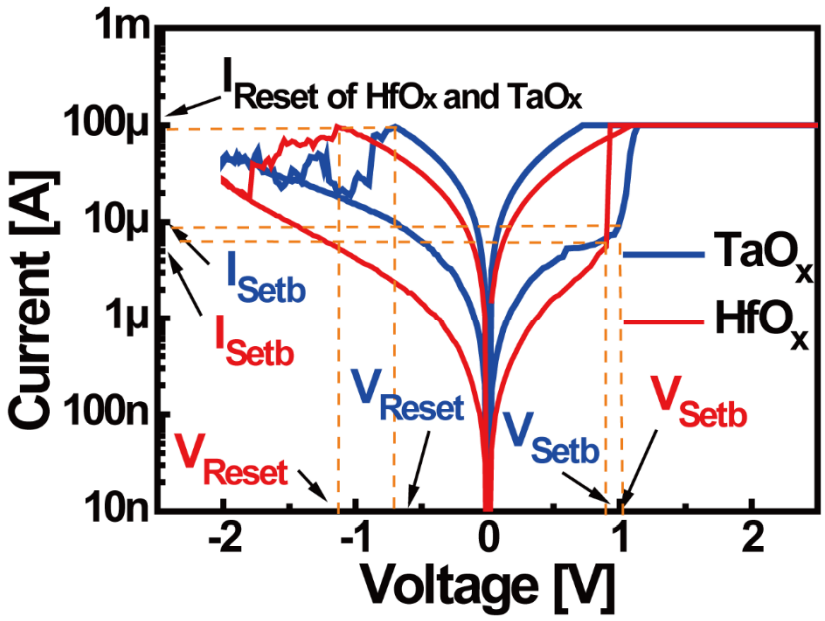
M. Kamiya et al., IEDM 2012
L. Goux et al., VLSI 2013

Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- Set and reset power requirement



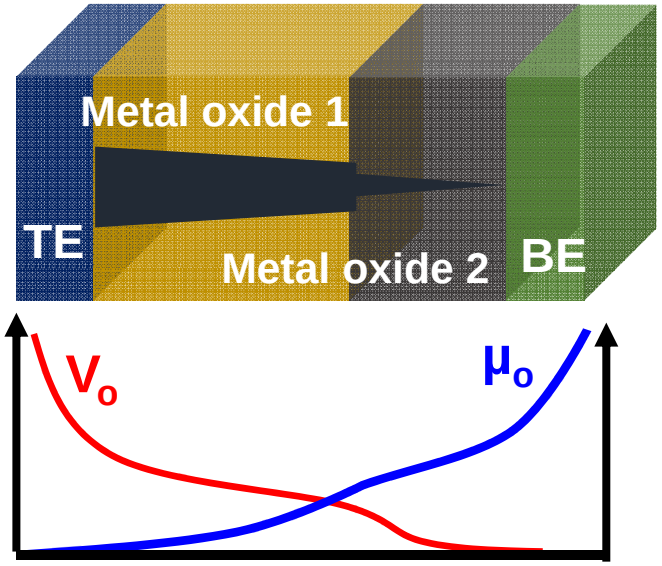


- ✓ Set power of HfO$_x$ was smaller than TaO$_x$
- ✓ Reset power of HfO$_x$ was higher than TaO$_x$

Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- Desirable ReRAM structure



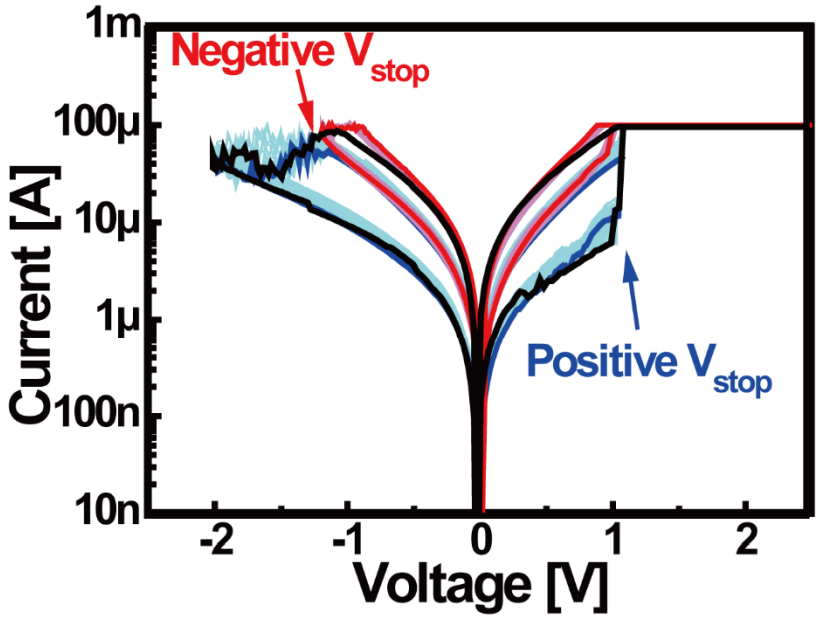
- Different chemical potential
- Higher set power of metal oxide 2
- Higher reset power of metal oxide 1

✓ Then, filament can be formed with two-step set operation

Triple-layer ReRAM of Two Oxides

2. Electrical Characteristics

- Two filament formation and rupture

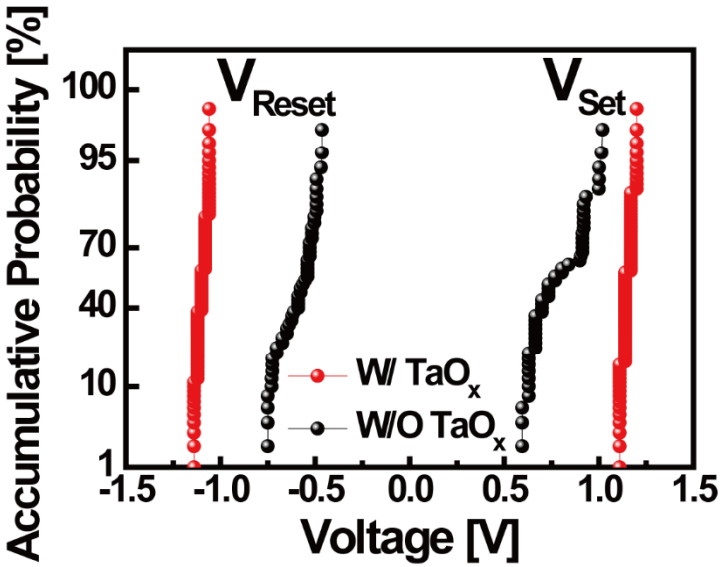


- ✓ To form TaO_x filament, the critical voltage was required
- ✓ We can stop filament formation and rupture

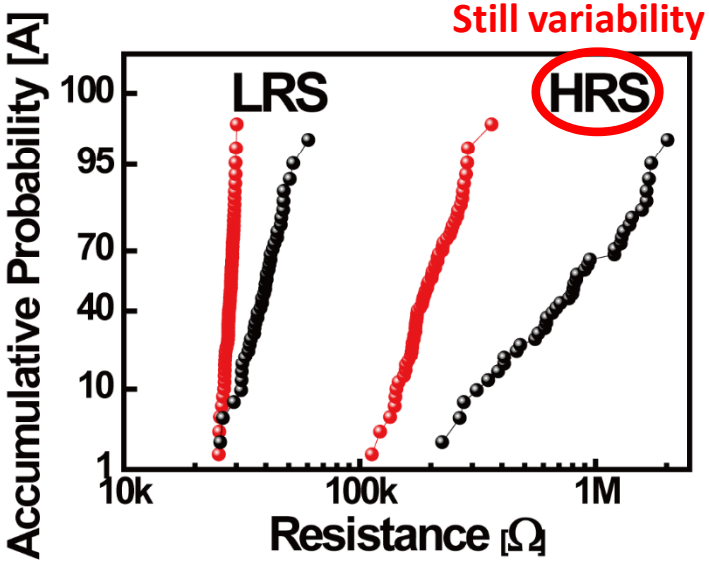
Triple-layer ReRAM of Two Oxides

3. Improved Switching uniformity

- Bi-layer ReRAM vs. Triple-layer ReRAM



- $STD(\sigma)/AVG_{Reset}=0.023$
- $STD(\sigma)/AVG_{Set}=0.023$



- $STD(\sigma)/AVG_{LRS}=0.04$
- $STD(\sigma)/AVG_{HRS}=0.26$

✓ To form TaO_x filament, the critical voltage was required.

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- **Gradual set operation ReRAM**
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  - **Improved Switching Uniformity**
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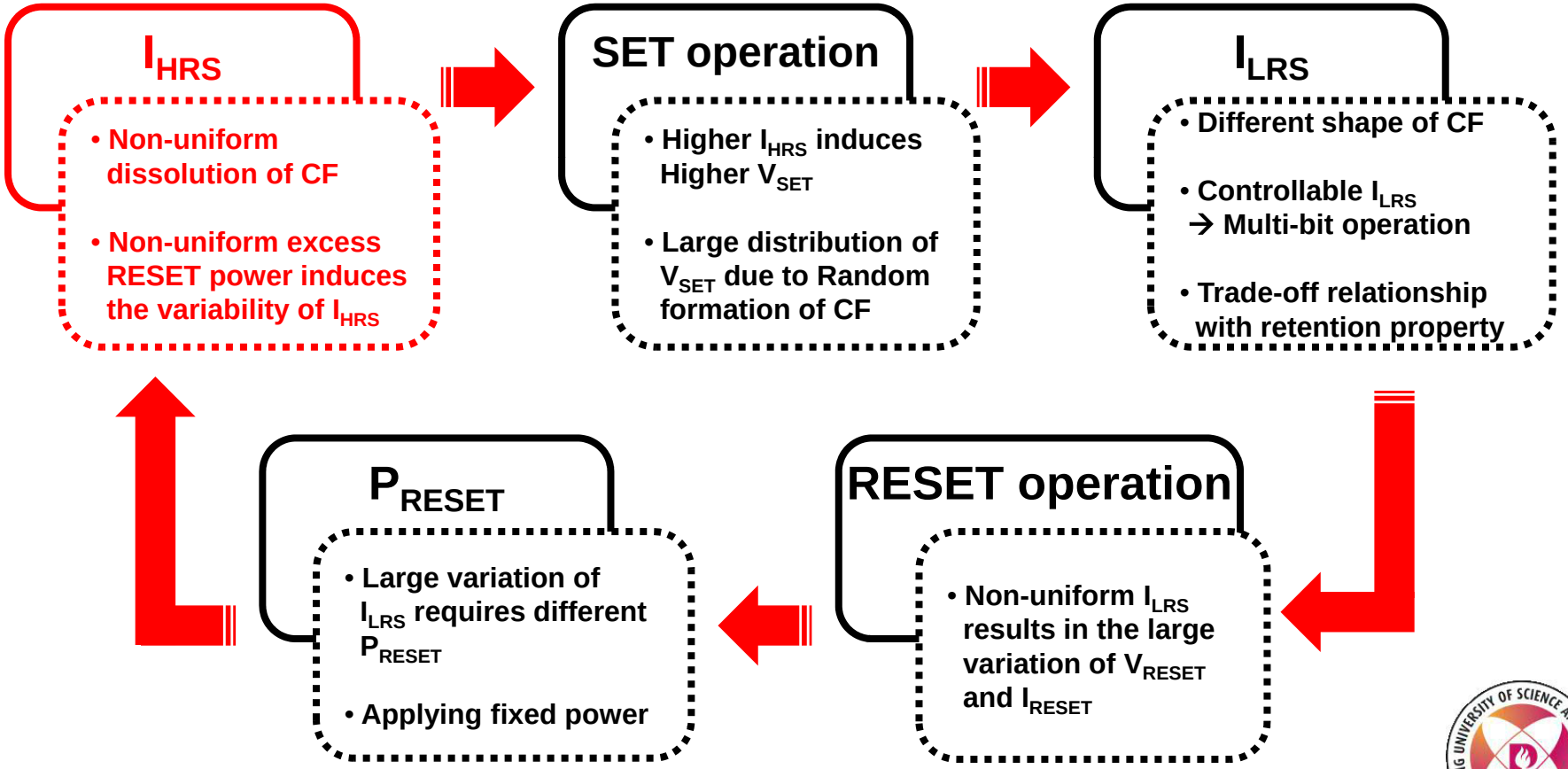
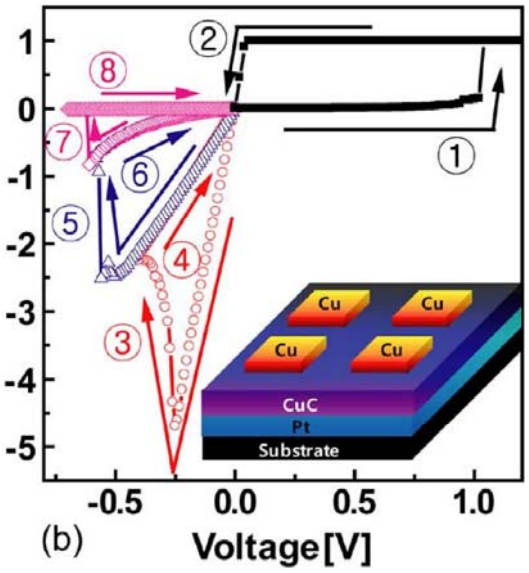
Introduction

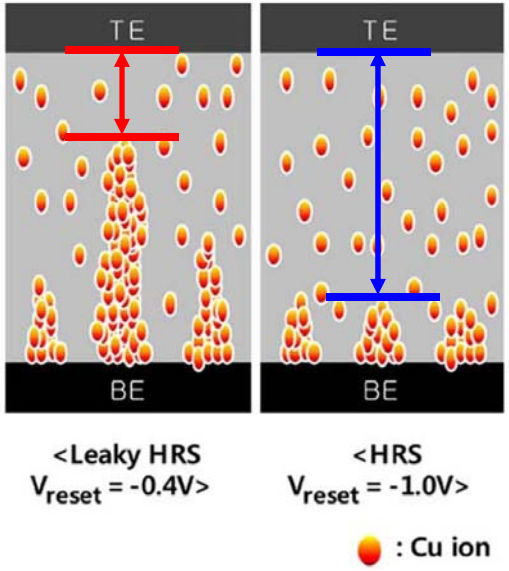
- **Motivation**
  - Chain Relationship for Variability Degradation

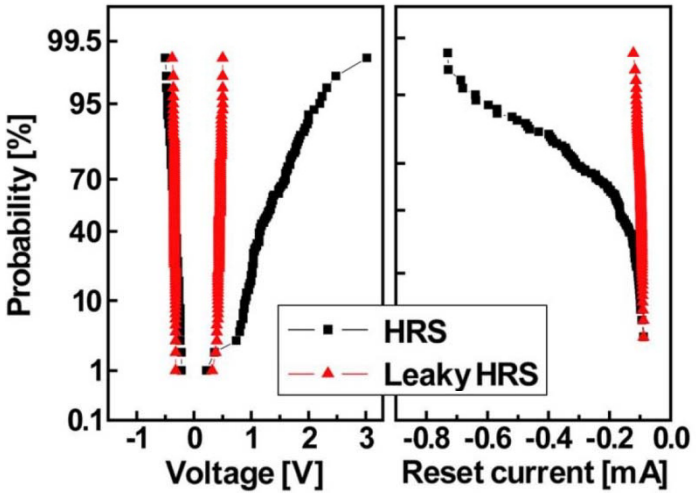


Highly Reliable Resistive Switching

1. Motivation for HRS stability







✓ **Defective HRS induces reliable switching!**

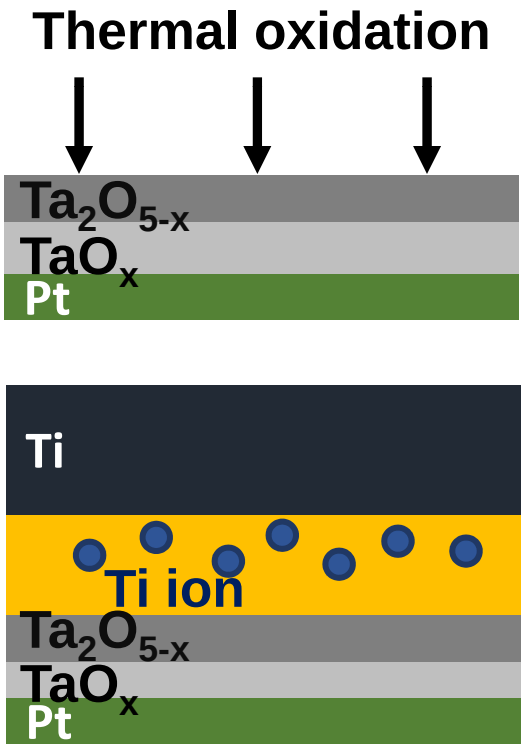
✓ **But, small on/off ratio was exhibited!**

J. Park et al., Electron Device Lett. 2010

ReRAM for Gradual Set Operation

1. Experimental
on 250 nm via-hole pattern substrate

- SiO_2 deposition by PECVD
- Pt BE deposition by sputter
- SiO_2 deposition by PECVD & 250 nm Patterning
- TaO_x (3.5 nm) deposition in Ar & O_2 ambient by RF sputtering
- **Thermal annealing in O_2 ambient by RTA**
- HfO_x (4 nm) deposition by ALD
- Ti top electrode deposition
- **Ultra-high vacuum annealing by RTA**
- **Defect engineered Ti/HfO_x/TaO_x/Pt ReRAM**

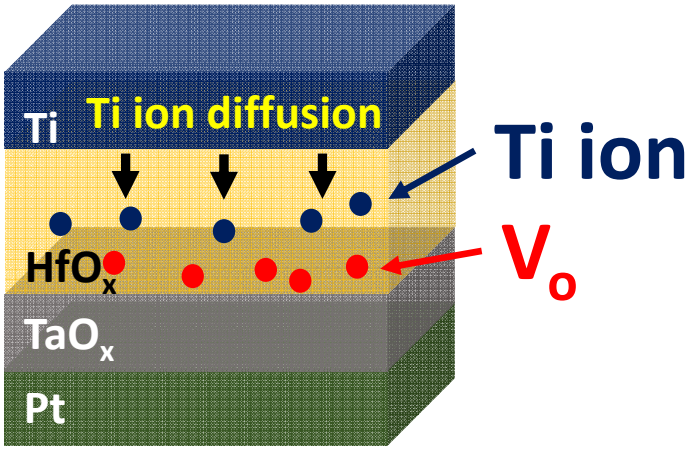


H. Zhang et al., Appl. Phys. Lett 2010

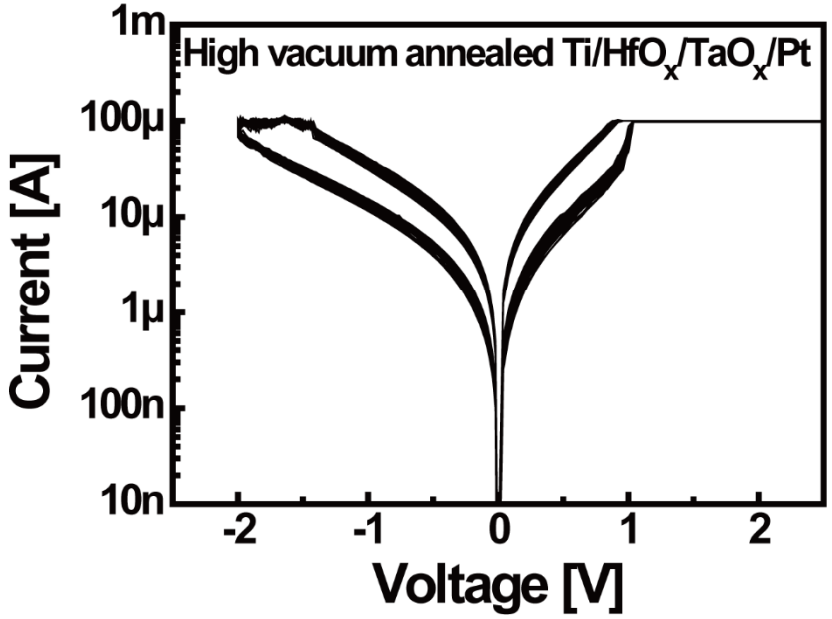
ReRAM for Gradual Set Operation

2. Electrical characteristics

- Ultra-high vaccum annealing for Ti ion diffusion



3 min annealing

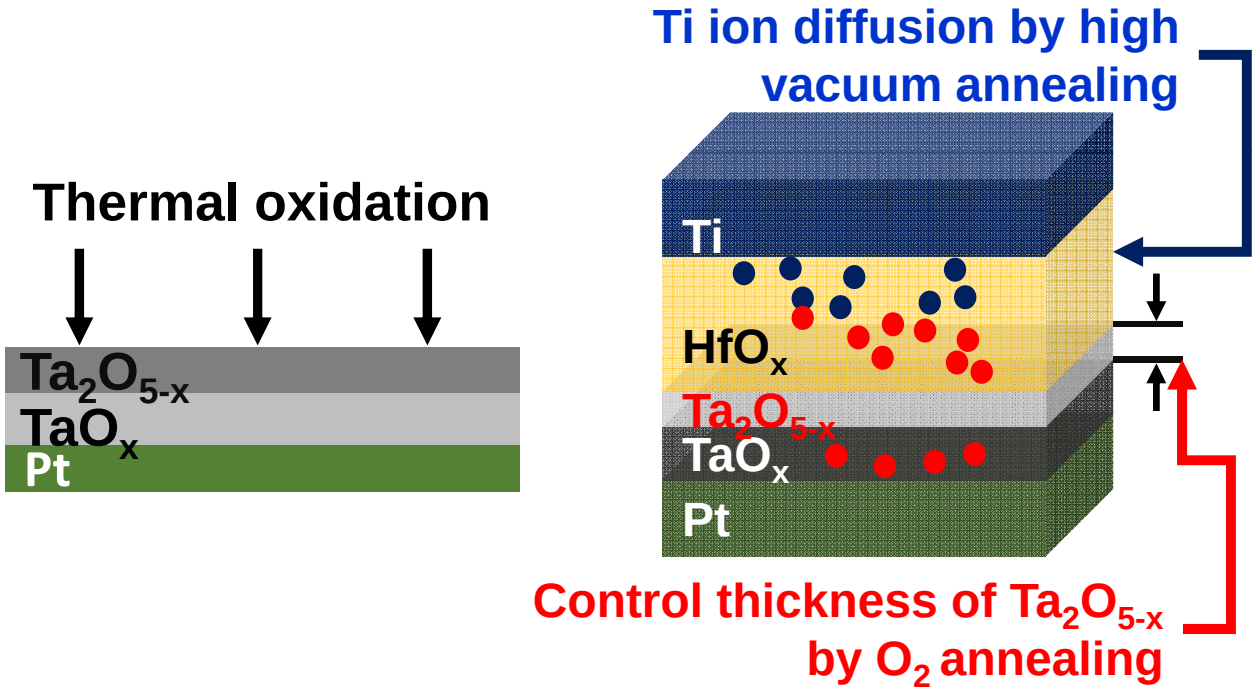


- ✓ Highly reliable resistive switching!
- ✓ But, poor on/off ratio owing to defective HRS

ReRAM for Gradual Set Operation

2. Electrical characteristics

- Oxygen thermal annealing for insulating Ta_2O_{5-x}



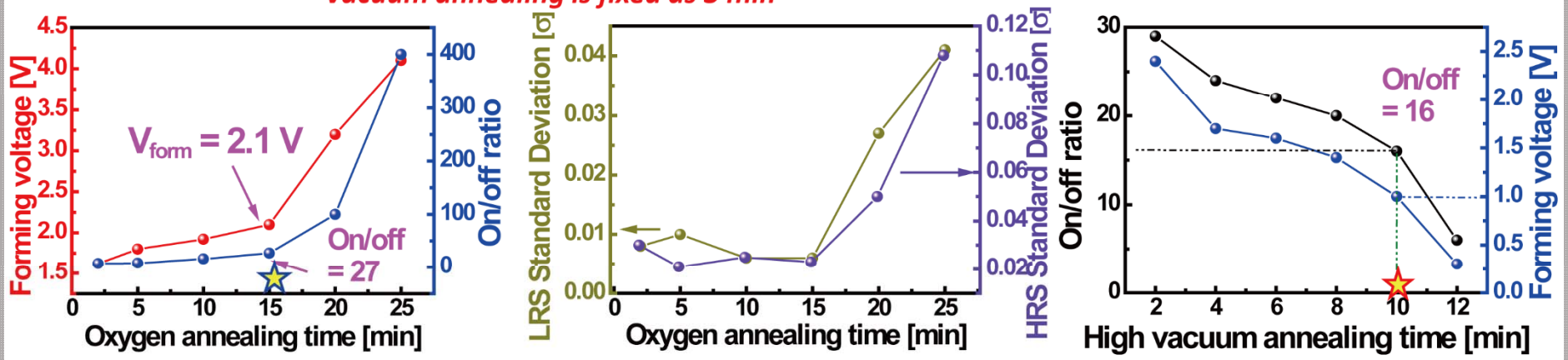
✓ Insulating Ta_2O_{5-x} will increase HRS for higher on/off ratio

ReRAM for Gradual Set Operation

2. Electrical characteristics

- For reliable switching with on/off & forming-less

- *Vacuum annealing is fixed as 3 min*



- O_2 thermal annealing improve on/off ratio
- Up to 15 min, no degradation of LRS and HRS STDs
- Ultra-high vaccum annealing for forming-less ReRAM

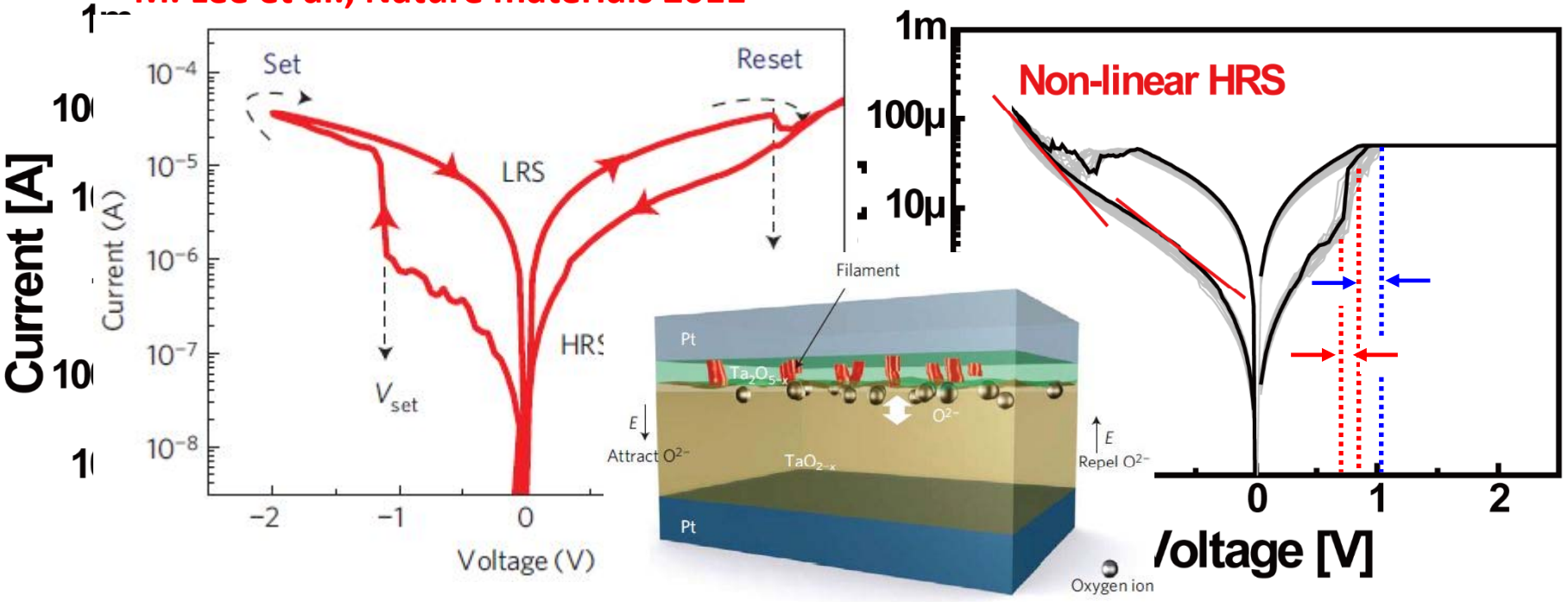
✓ **Highly reliable switching without degradation, even no initial forming operation**

ReRAM for Gradual Set Operation

2. Electrical characteristics

- For reliable switching with on/off & forming-less

M. Lee et al., Nature materials 2011

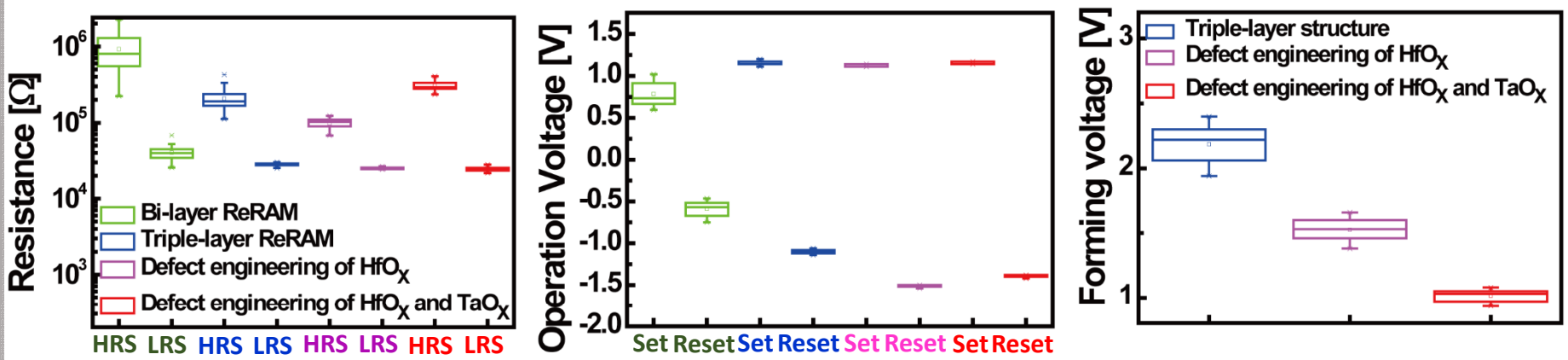


- ✓ Not stepwise set operation, gradual set operation
- ✓ Excellent reliability

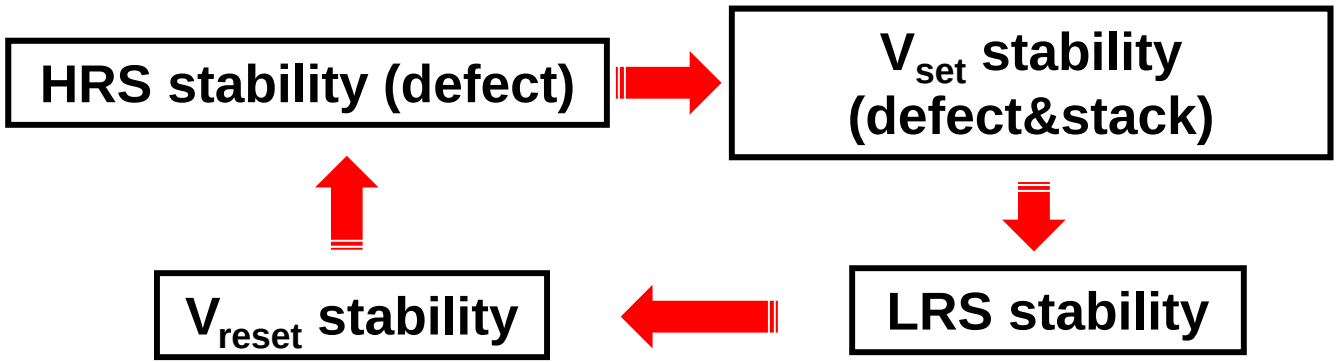
ReRAM for Gradual Set Operation

3. Improved switching uniformity / Retention

- Switching uniformity

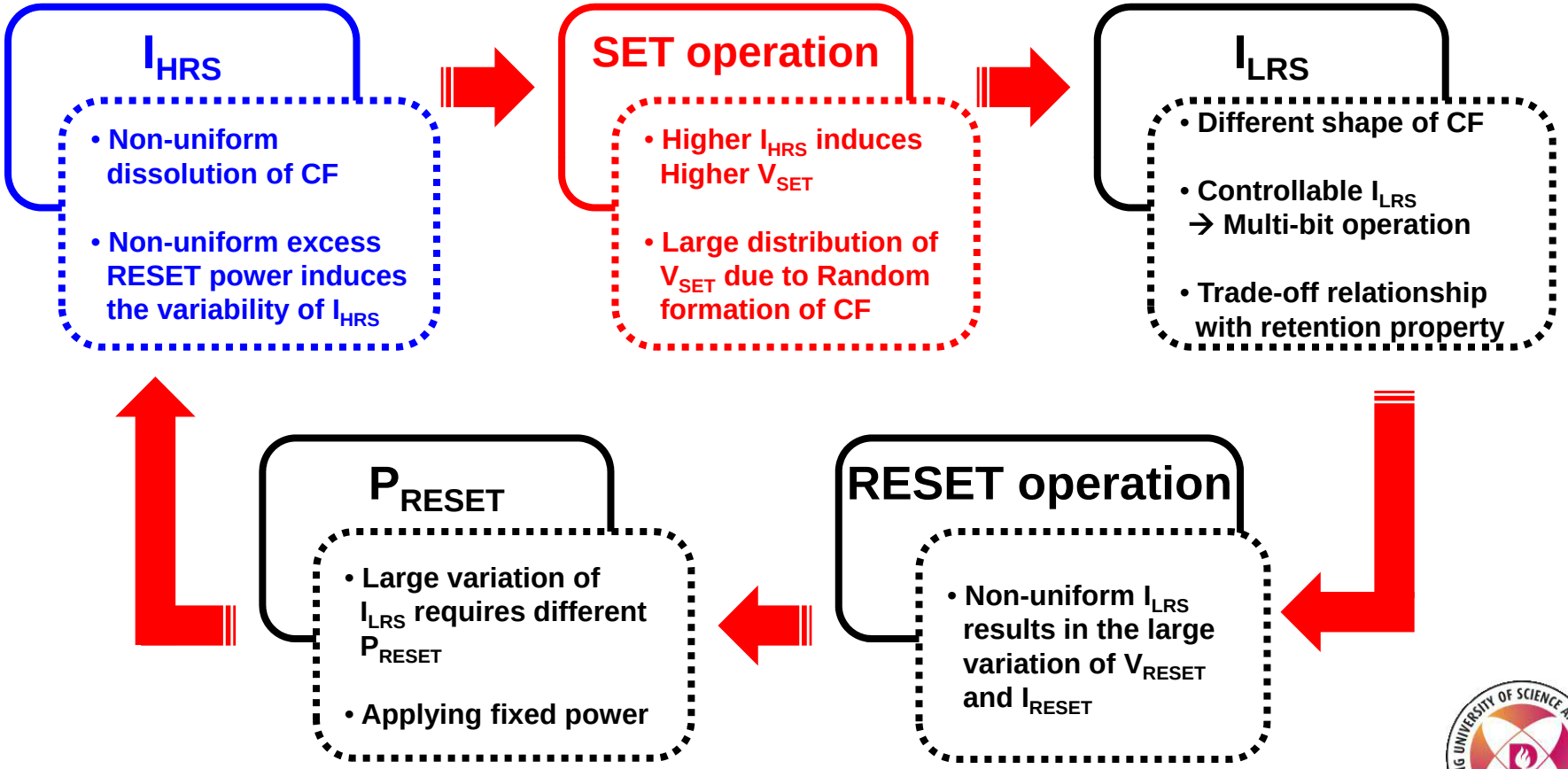


✓ High defect density ➡ HRS stability & no forming operation



Introduction

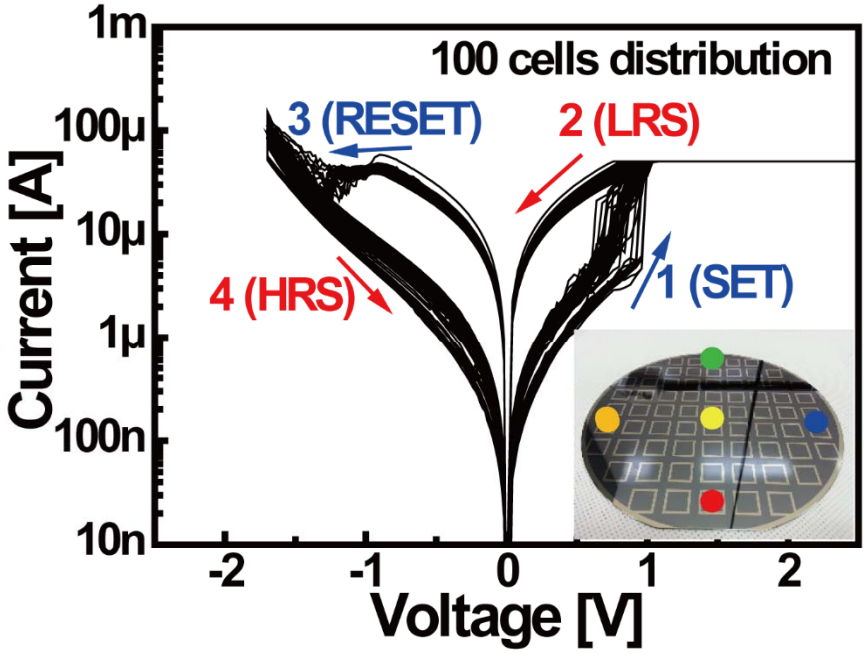
- **Motivation**
  - Chain Relationship for Variability Degradation



ReRAM for Gradual Set Operation

3. Improved switching uniformity

- Excellent cell to cell distribution



✓ Cell to cell distribution of 4-inch wafer

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- **Conclusion**

Conclusion

- **Two-step set of the triple-layer ReRAM**
  - **Two filaments formation and rupture due to different filament formation abilities for reliable set operation**
  - **Stable set operation induces stable LRS**
  - **But, forming operation & still HRS variability**
- **Defect engineering of the triple-layer ReRAM**
  - **HfO_x defect engineering for HRS stability & forming-less operation by ultra-high vacuum annealing**
  - **TaO_x defect engineering for on/off ratio by oxygen thermal annealing**
  - **Lower operating current (50 uA) was achieved**

Thank you for your attention!!

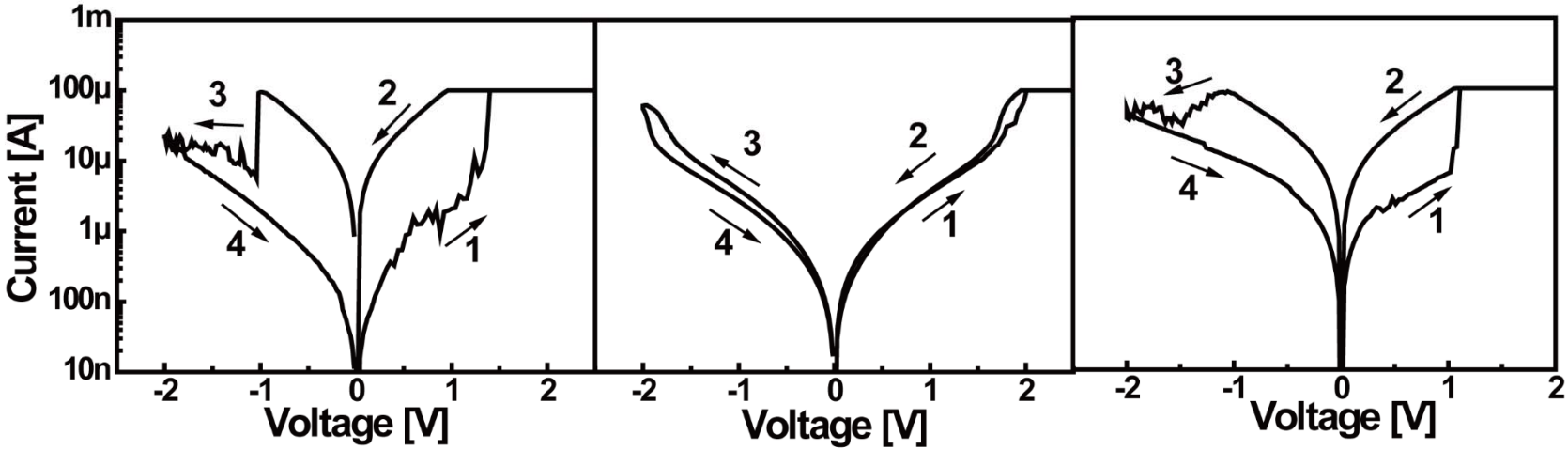
Acknowledgement

This work was supported by R&D program of Korea Ministry of Knowledge Economy and POSTECH-Samsung Electronics ReRAM cluster Research.

Back-up slide

Electrical Characteristics

- Inserting various metal oxide layers



Ti/HfO$_x$/AlO$_x$/Pt Ti/HfO$_x$/TiO$_x$/Pt Ti/HfO$_x$/TaO$_x$/Pt

- ✓ Inserting AlO$_x$ exhibited unstable HRS
- ✓ Inserting TiO$_x$ exhibited small on/off ratio