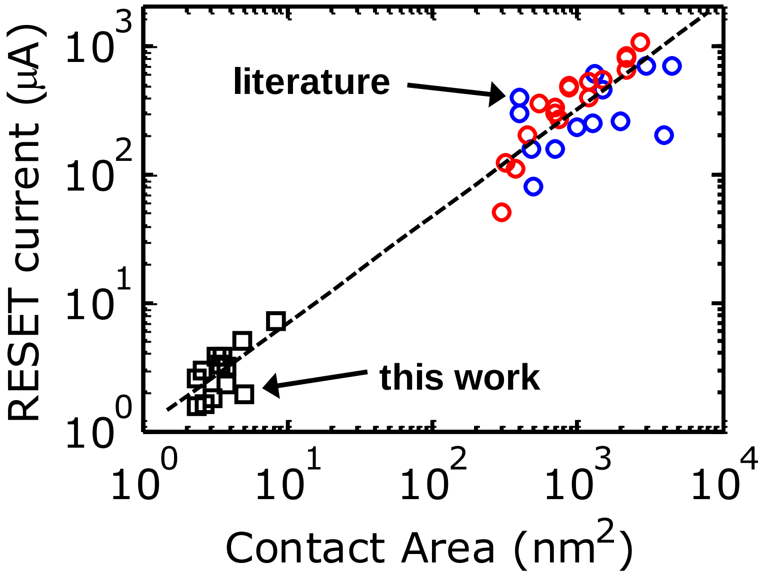
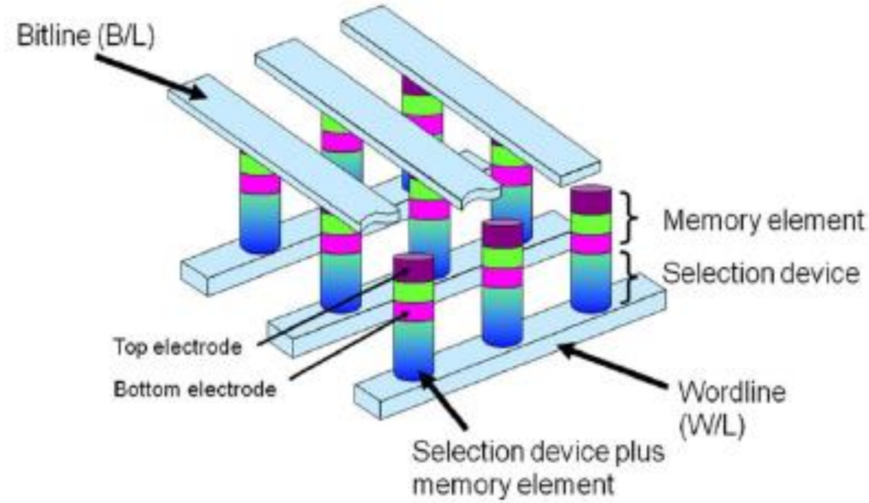
# L5: Resistive RAM I

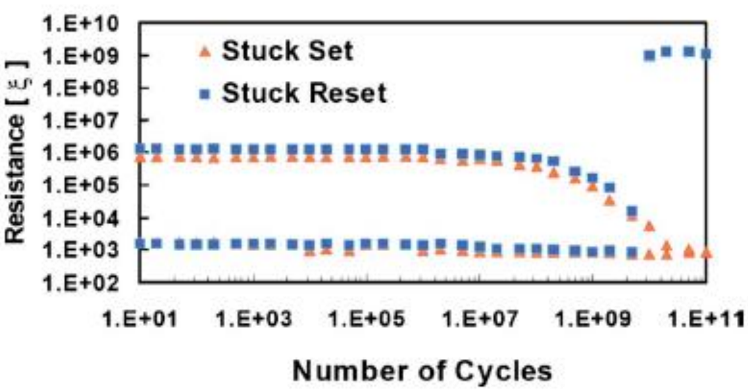
# Recap



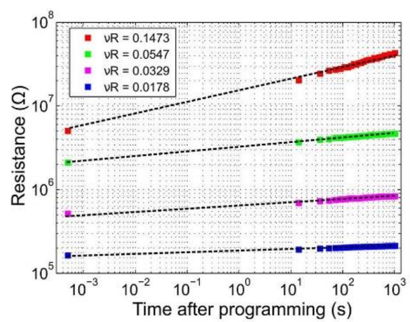
RESET current (μA)
literature
this work
Contact Area (nm²)

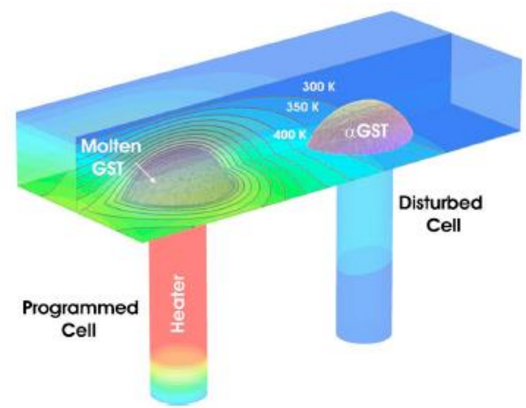
Bitline (B/L)
Memory element
Selection device
Top electrode
Bottom electrode
Wordline (W/L)
Selection device plus memory element

Stuck Set
Stuck Reset
Resistance
Number of Cycles

Resistance (Ω)
Time after programming (s)

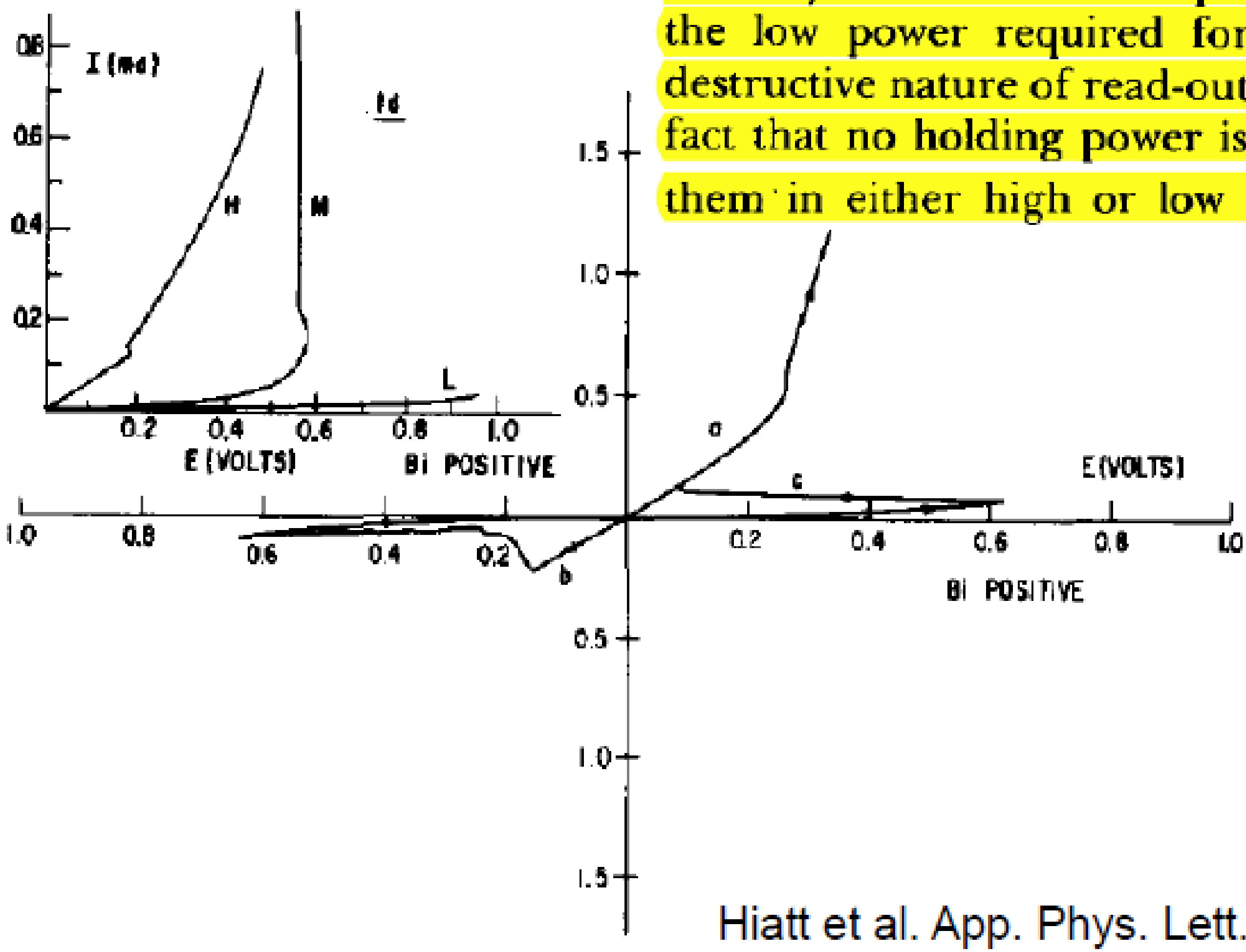



Molten GST
300 K
350 K
400 K
αGST
Disturbed Cell
Programmed Cell
Heater

# Outline

- Introduction
  - History
  - pros and cons
  - device structure
- Unipolar vs. bipolar
- Switching mechanisms
- Cation switching
- Anion switching
- Forming, set and reset

# History of RRAM

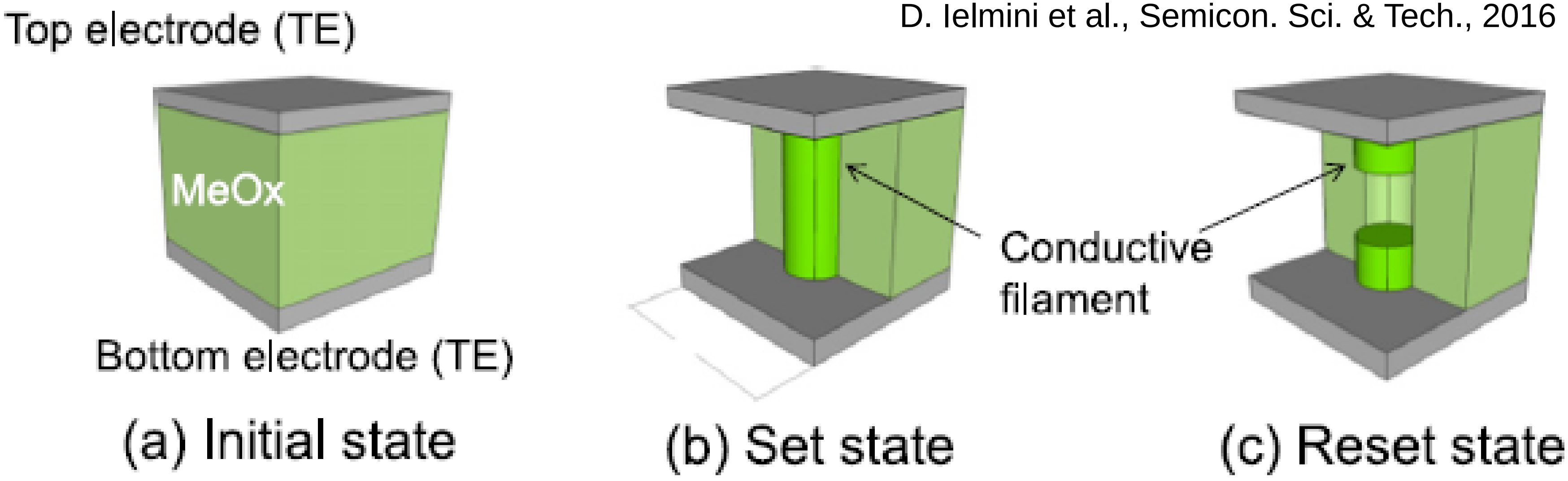


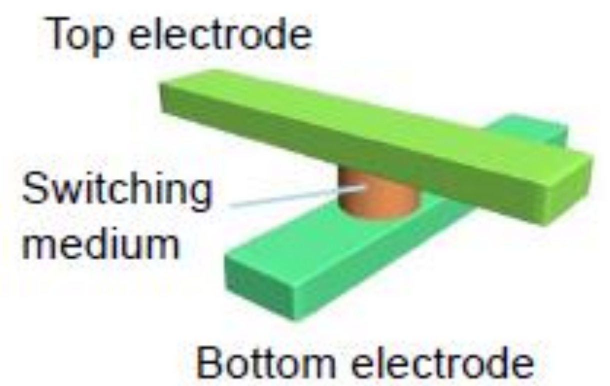

The possible use of Nb-$Nb_2O_5$-metal diodes, particularly Nb-$Nb_2O_5$-Bi diodes, in a computer memory is obvious. Their potential advantages are the low power required for switching, the non-destructive nature of read-out of the device and the fact that no holding power is required to maintain them in either high or low conductivity state. At

Hiatt et al. App. Phys. Lett. 6, 106, 1965

# Resistive Switching

D. Ielmini et al., Semicon. Sci. & Tech., 2016

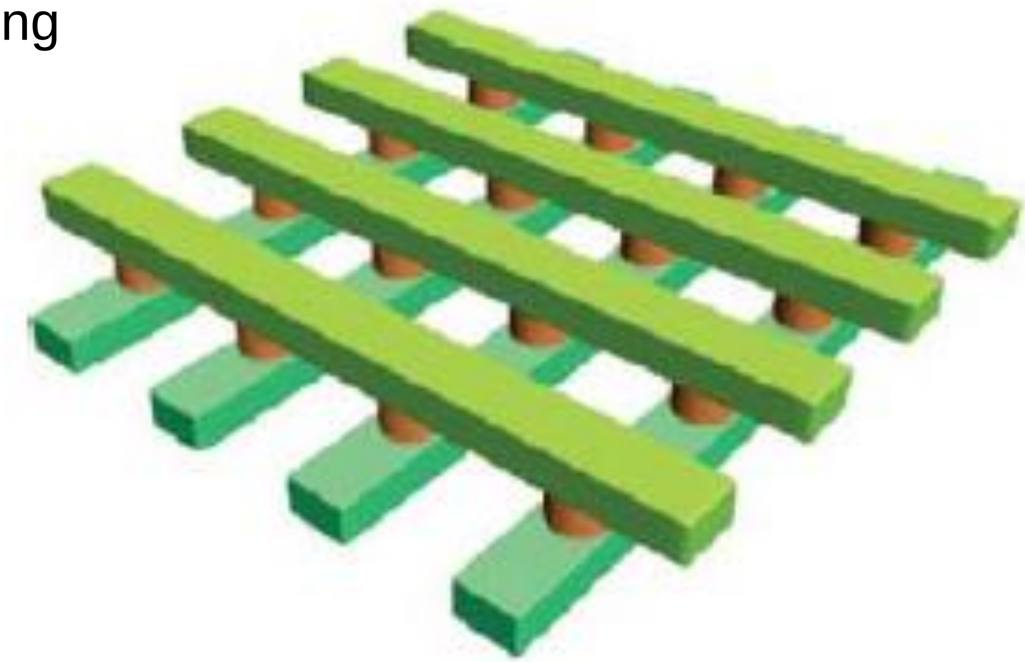


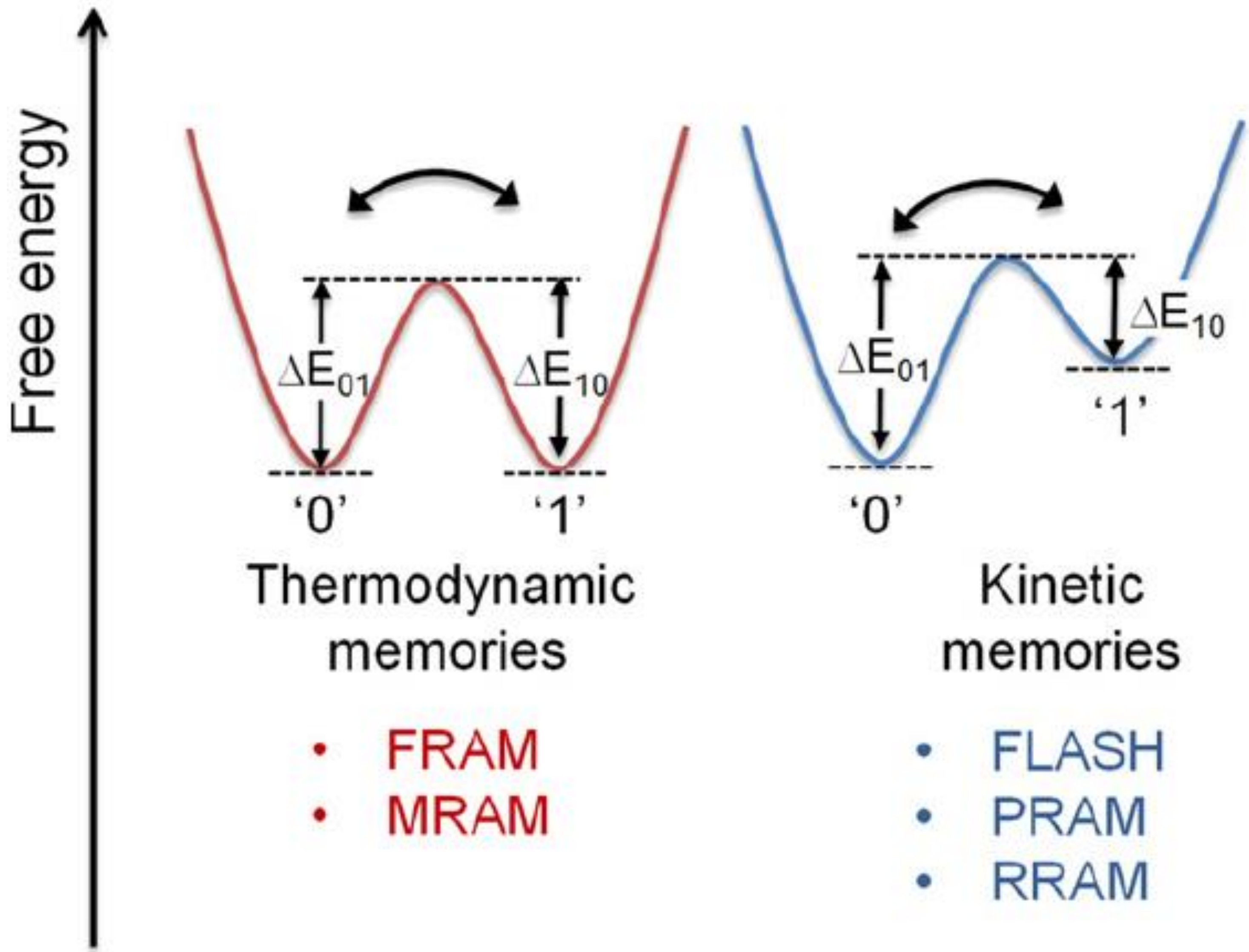

- E-field and Joule heating induced ionic movement
- Formation and dissolution of a conductive filament (CF)
- Compliance needed to prevent breakdown

# RRAM Pros and Cons

- Simple structure
  - two-terminal device
  - not limited by transistor scaling
- Ultra-high density
  - Cell size $4F^2$
  - 3D stackable
  - terabit potential
  - Multi-level cell
- Large connectivity
- memory, logic and neuromorphic applications

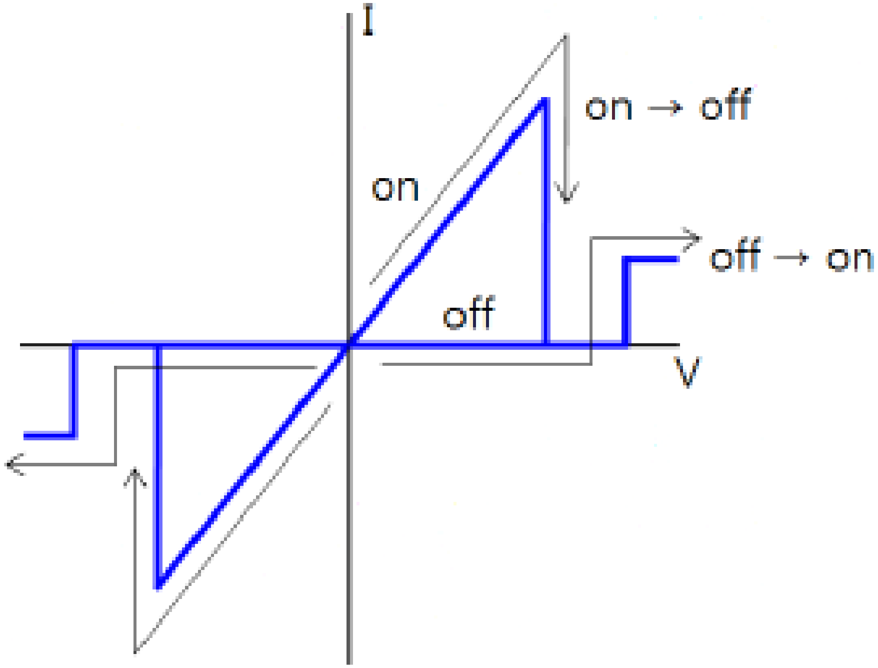


# RRAM Activation Energy

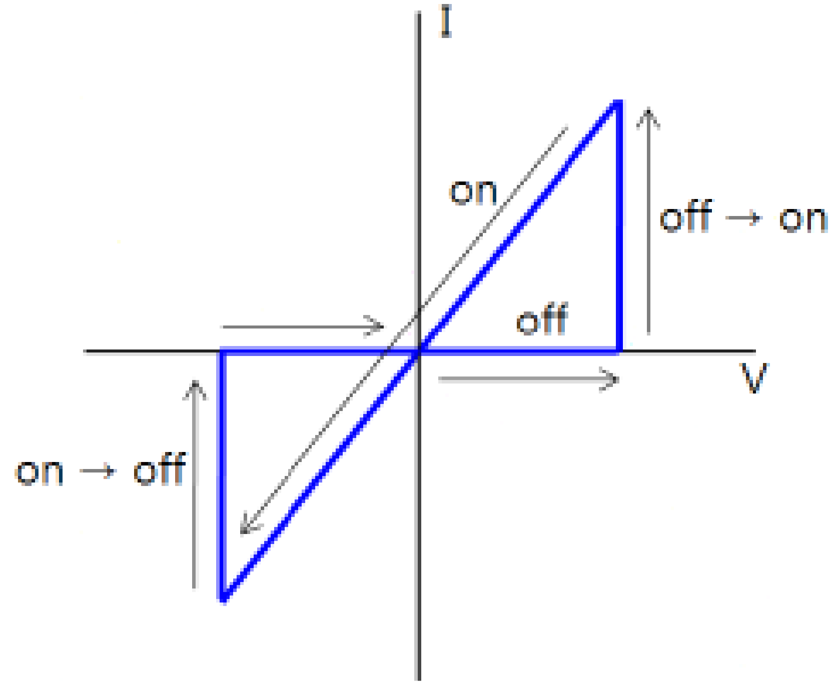


# Unipolar vs. Bipolar

## Unipolar



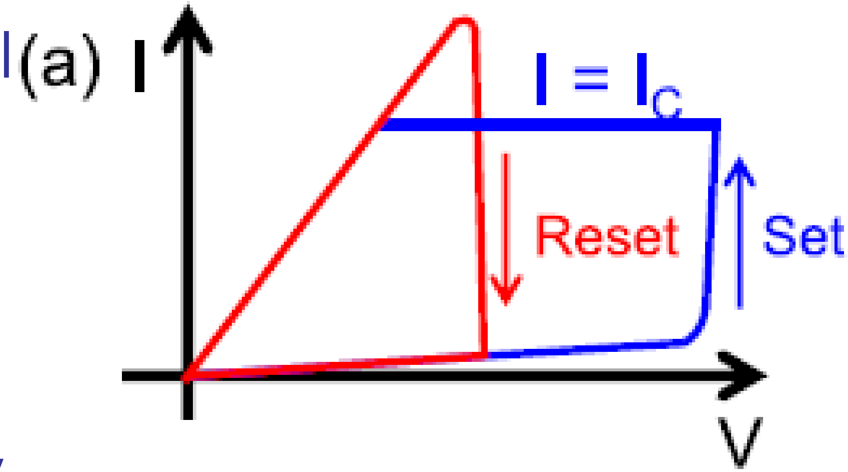

## Bipolar




- Unipolar: both set and reset are achieved by applying voltages of the ***same*** polarity
- Bipolar: set and reset are achieved by applying voltages of ***different*** polarity

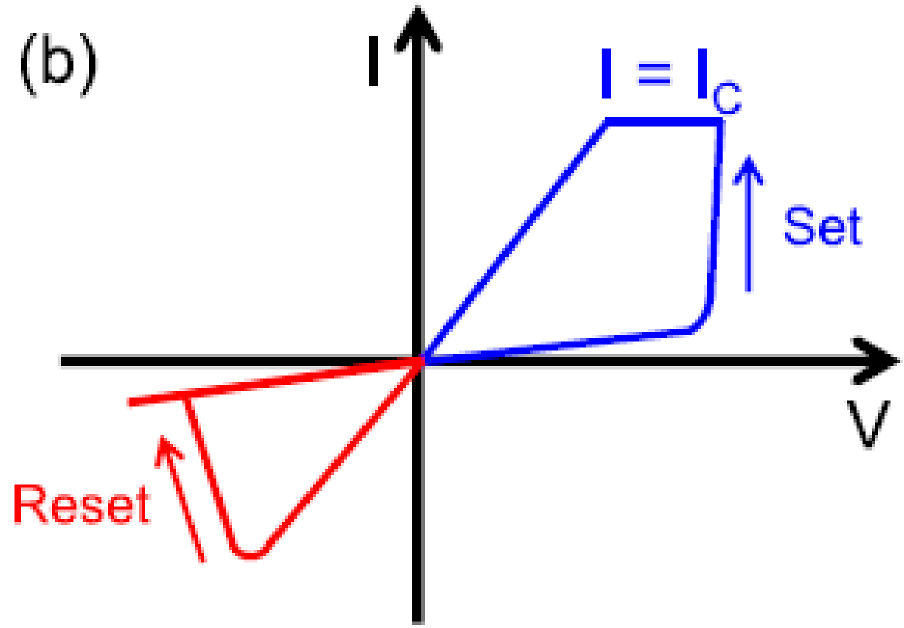
# Unipolar

- Thermally accelerated redox transitions
- Set: chemical reduction of metal oxides and CF re-connection
- Reset: oxidation of metallic filament and CF disconnection
- Preferred due to simple circuit and selection design in memory array
- Suffers from lower uniformity and low endurance

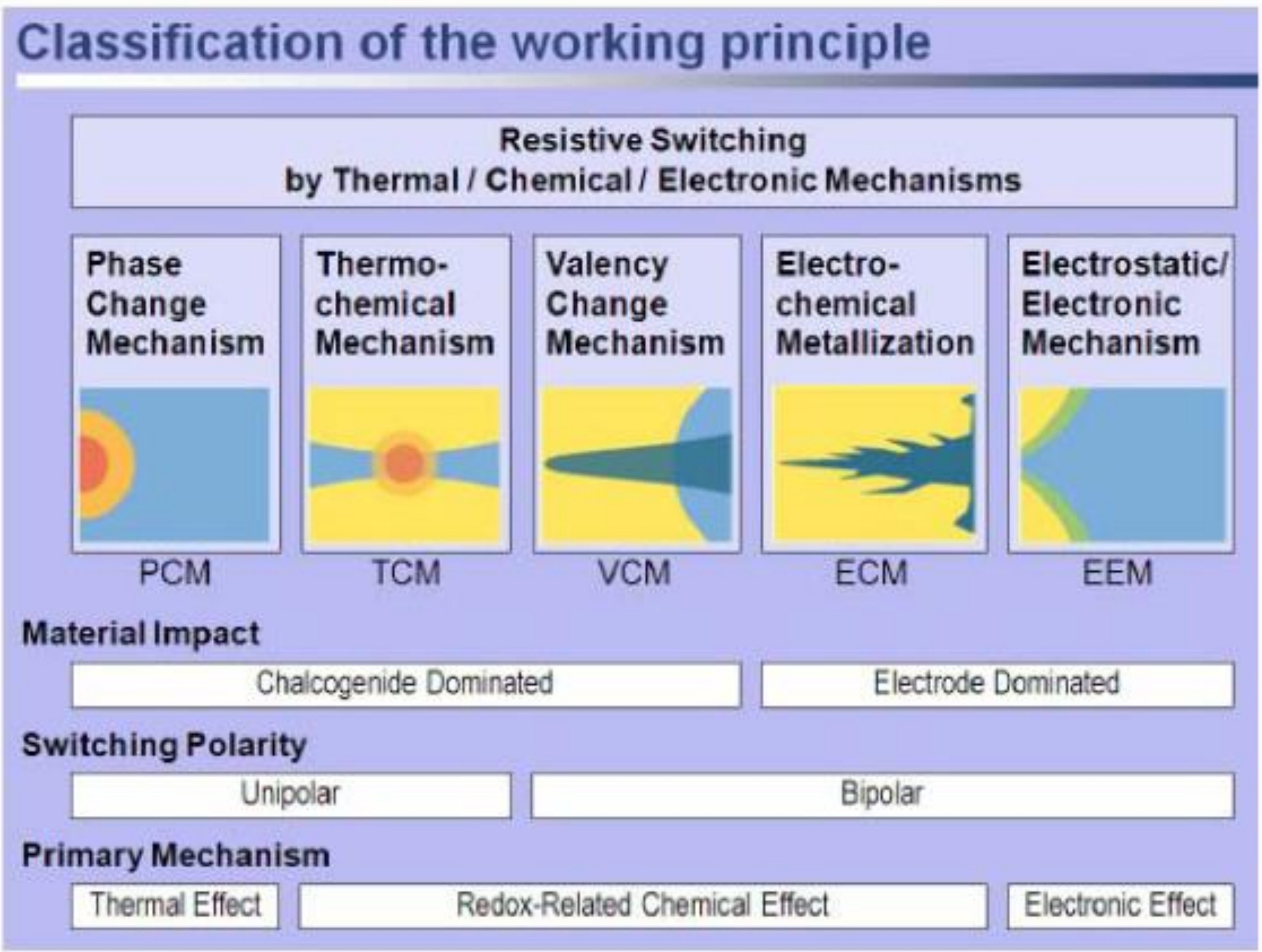


# Bipolar

- Depends on both temperature and E-field
- Reset: migration of ionized defects towards the –ve electrode → depletion region in the CF
- Set: injection of these defects back to the CF
- Better reliability and endurance
  - ionized defects are conserved during programming
- Current focus of most researches

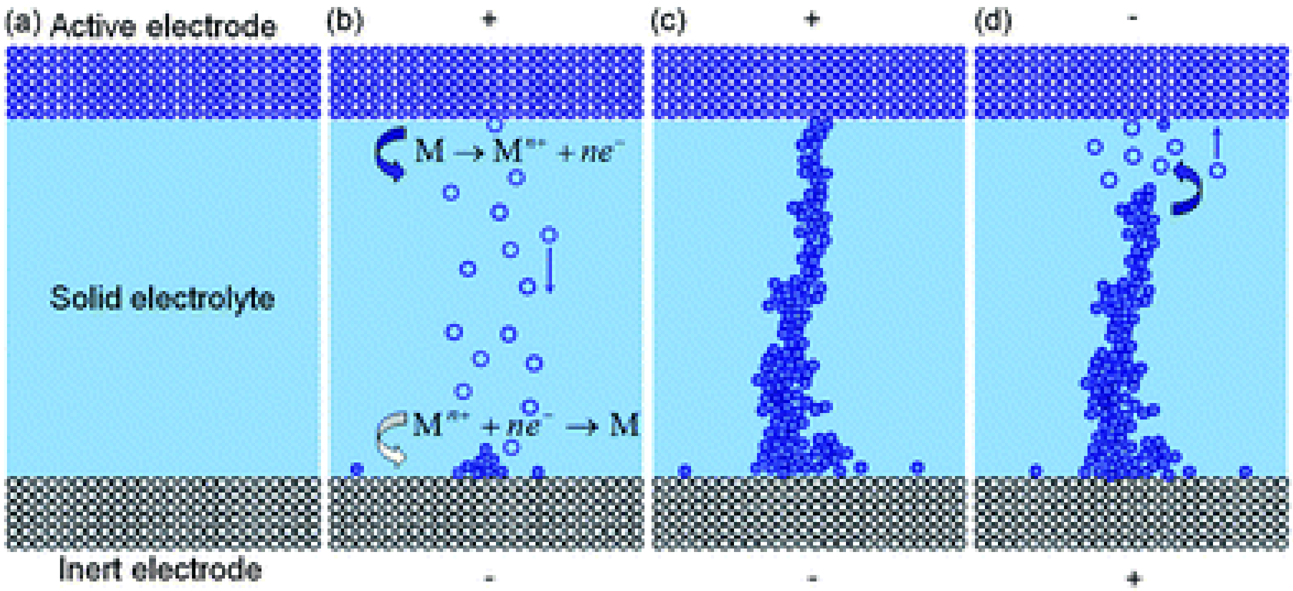


# RRAM Switching Mechanisms




ITRS_ERD workshop, April 2010

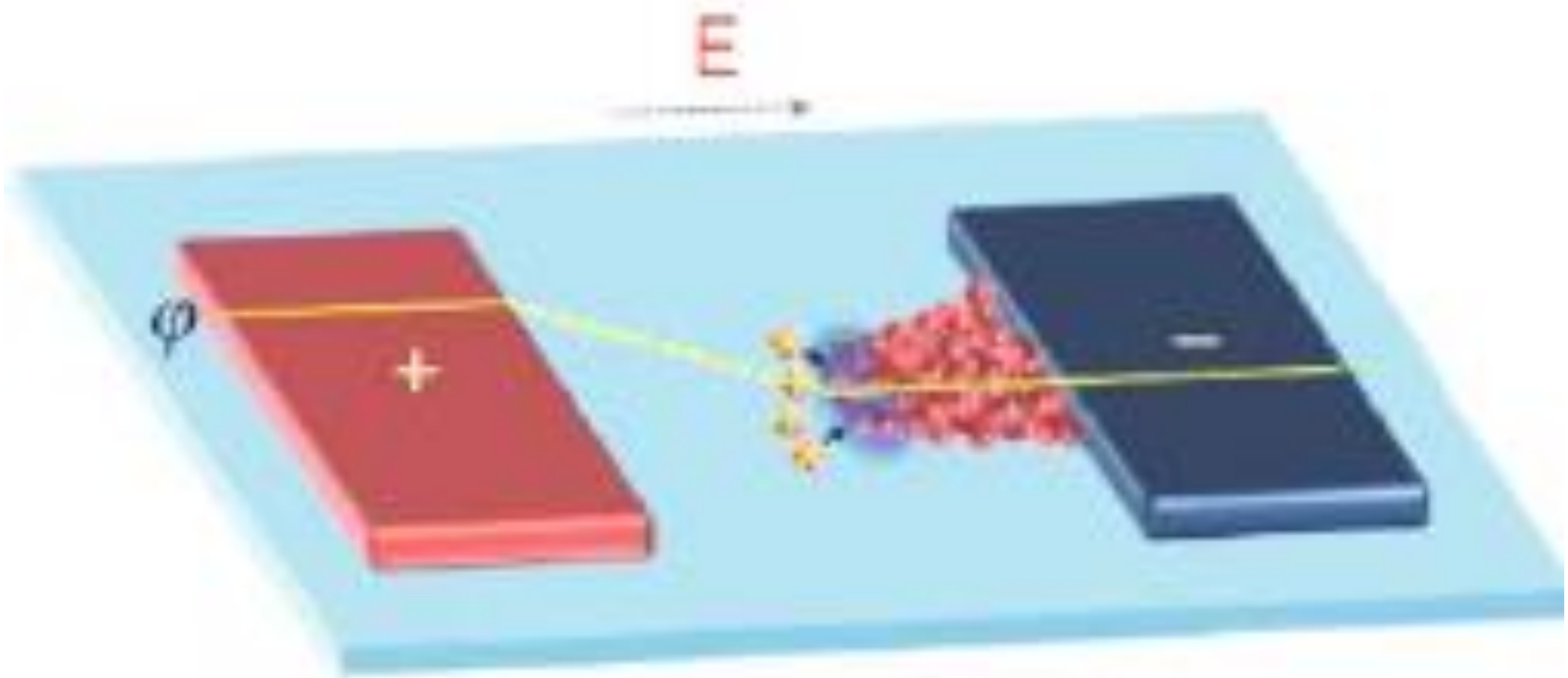
# Cation Switching




- Forming and dissolution of metallic filament inside a dielectric medium
- Mostly unipolar → thermally accelerated redox reaction
- Key parameters:
  - ion mobility $\mu$
  - redox reaction rate R

# Cation Switching Case I

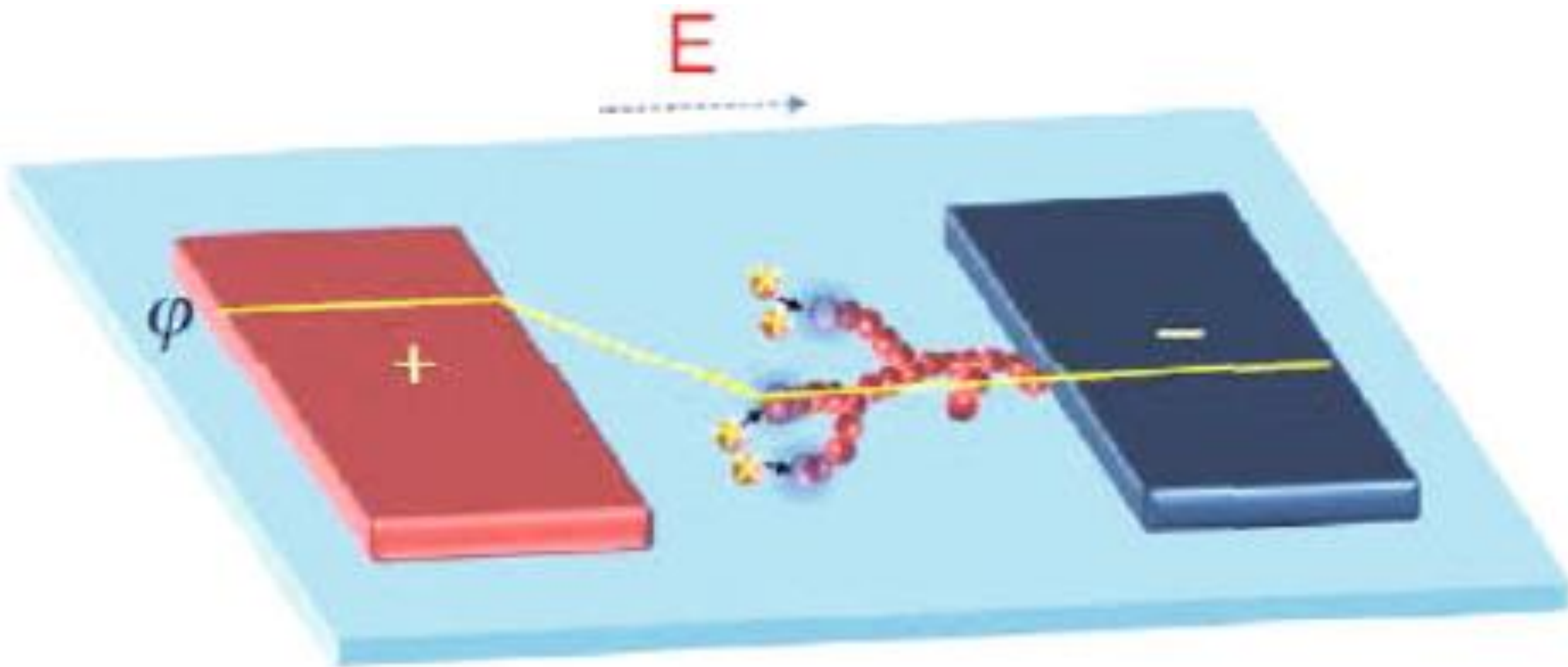
Yang et al., Nat. Comm., 2014




- High ion mobility μ and high redox rate R
- cations can reach anode (-ve) without reducing
- Filament **growth starts at anode**
- With large ion supplies (high R), **inverted cone** shaped filament

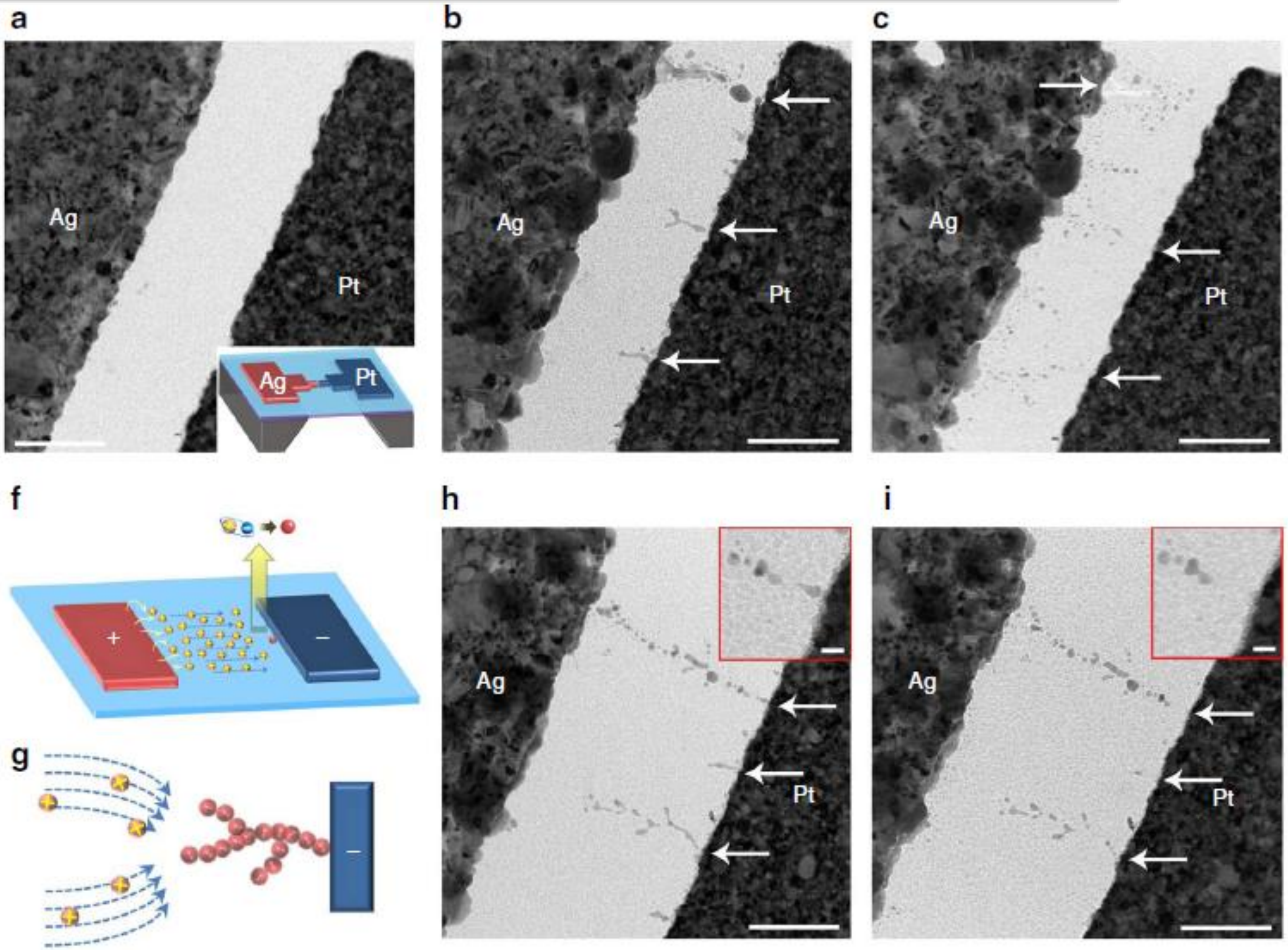
# Cation Switching Case II

Yang et al., Nat. Comm., 2014




- High ion mobility μ and low redox rate R
- Ions are **reduced at anode** electrode
- With limited ion supply (low R), reduction occurs at the edge → **branched growth** towards cathode

# In-situ TEM of Filament Movements



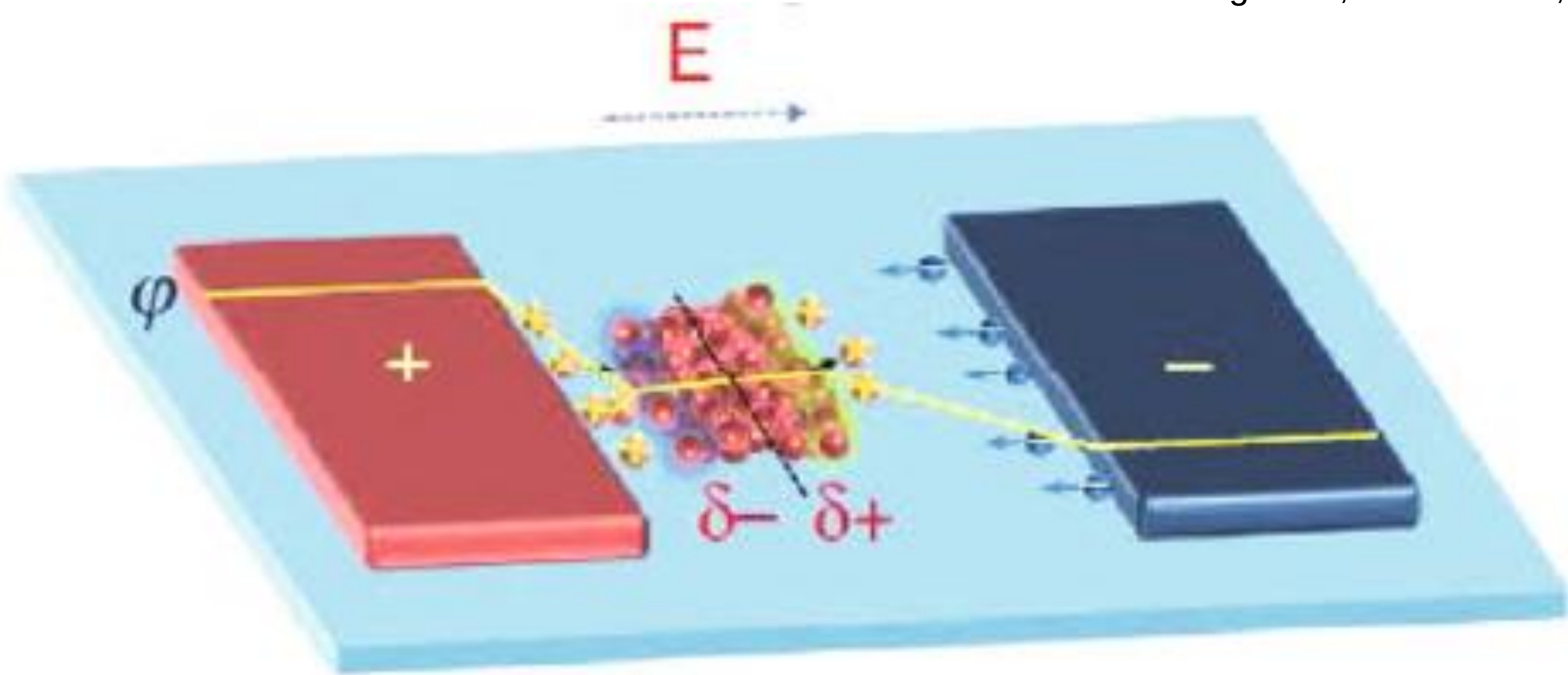

- High ion mobility μ and low redox rate R

Yang et al., Nat. Comm., 2012

- With limited ion supply (low R), reduction occurs at the edge → **branched growth** towards cathode

# Cation Switching Case III

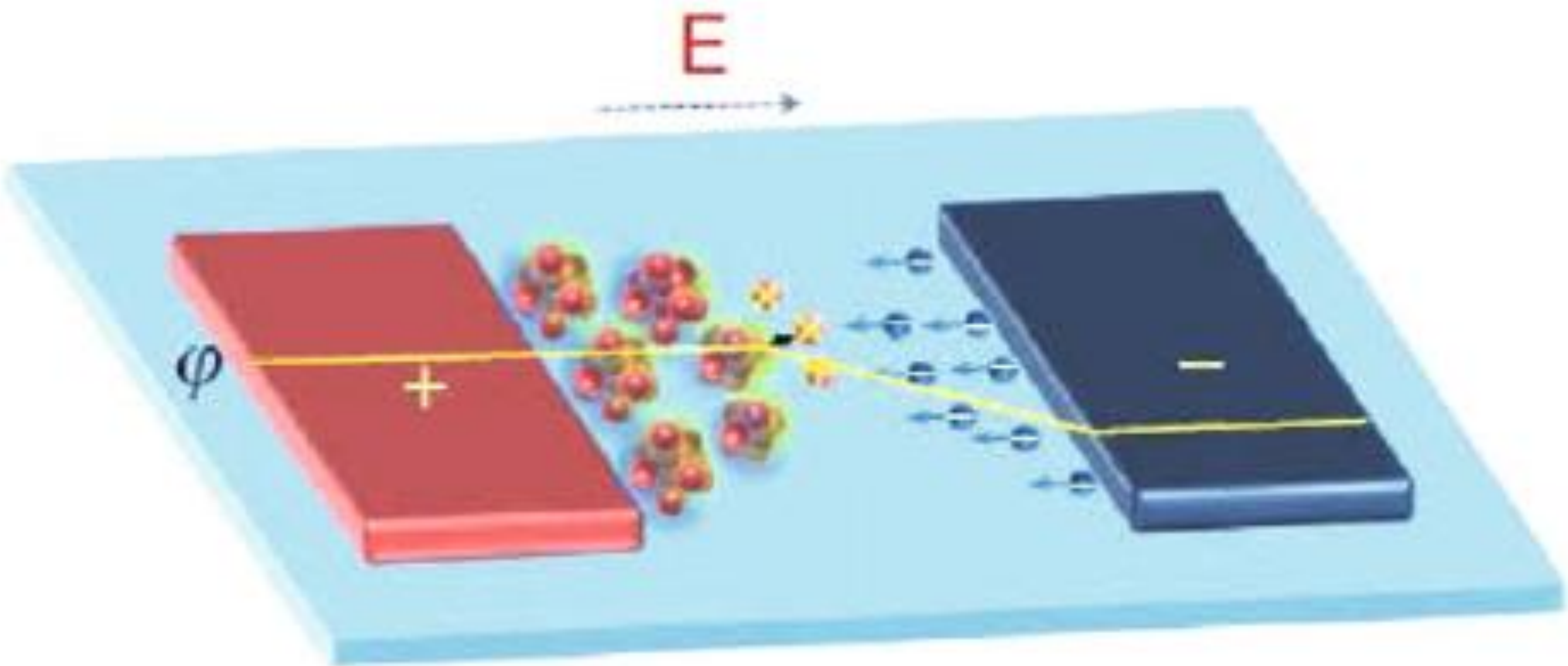
Yang et al., Nat. Comm., 2014




- Low ion mobility μ and high redox rate R
- Ions **nucleate inside dielectric**
- Incoming ions are **reduced at the site of nucleation** due to high redox rate
- **First** bridging the gap between nucleation and **cathode**
- **Then** filament growth towards **anode**

# Cation Switching Case IV

Yang et al., Nat. Comm., 2014



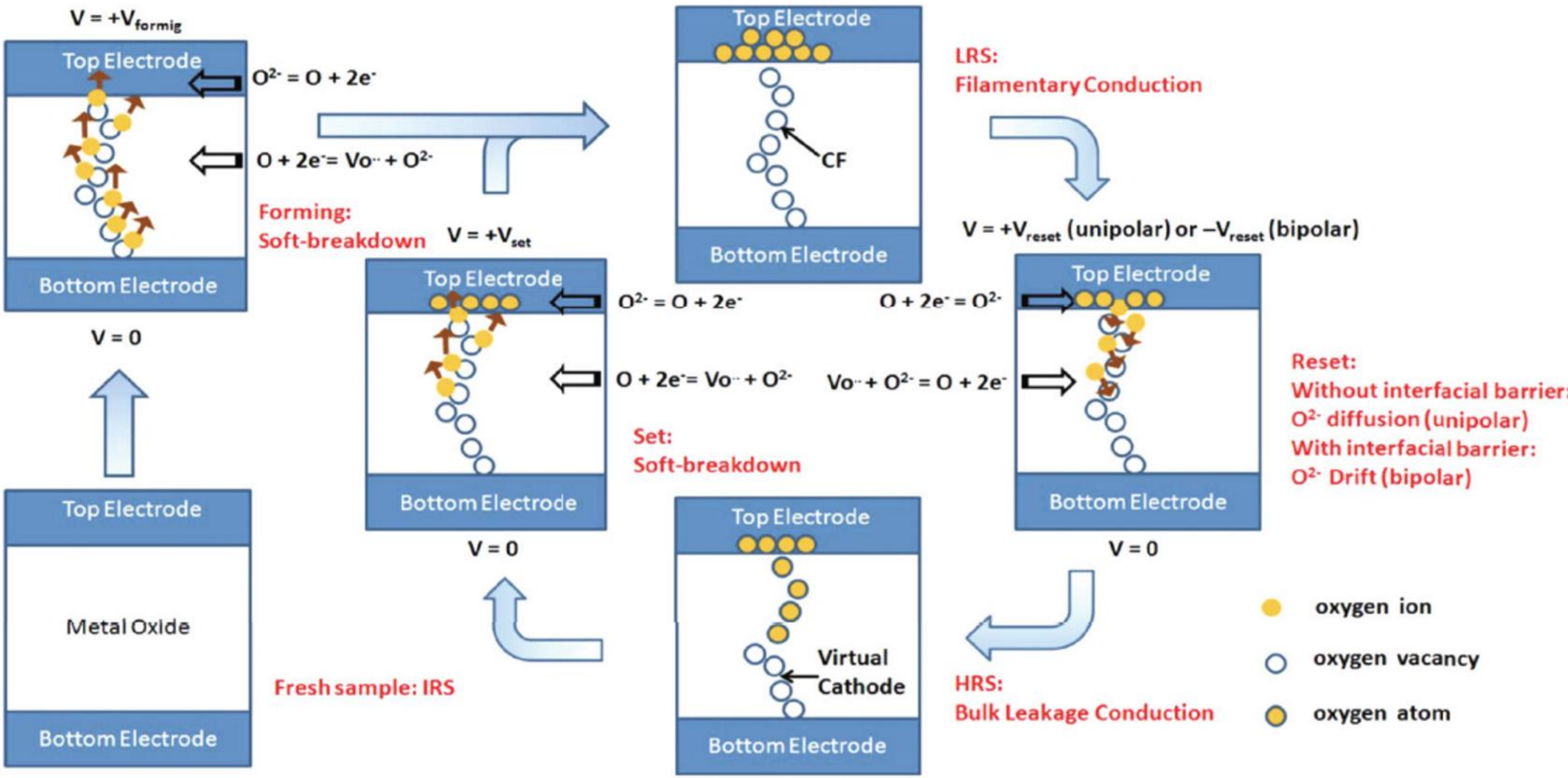

- Low ion mobility μ and low redox rate R
- Ions **nucleate inside the dielectric**
- Further growth through **cluster displacement** and repeated **splitting-merging process**

# Cation Summary

| | High μ | Low μ |
|---|---|---|
| **High R** | Inverted Cone from anode | Nucleate from middle, grows towards cathode and then anode |
| **Low R** | Branched growth from anode | graduate cluster displacement and splitting-merging |

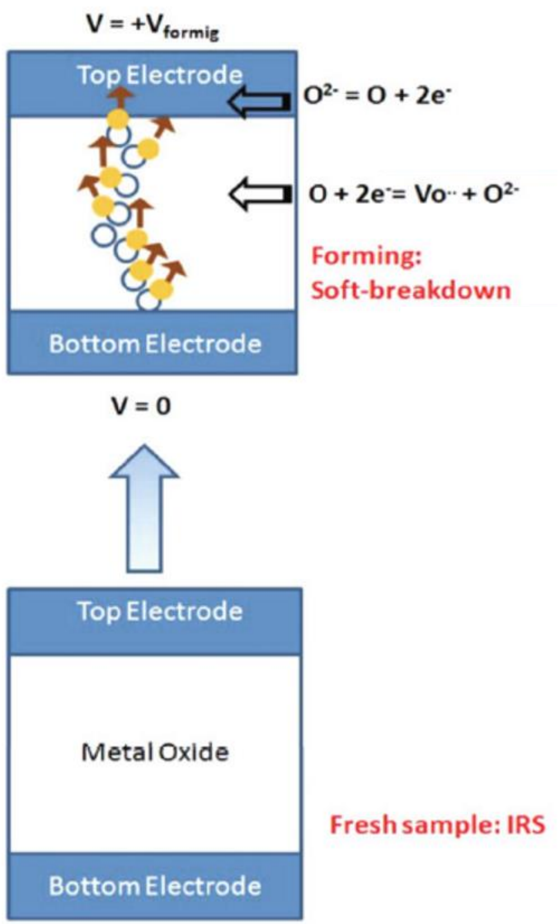
- High μ: growth starts at anode side
- low μ: growth starts inside dielectric
- high R: cone filament
- Low R: branched growth

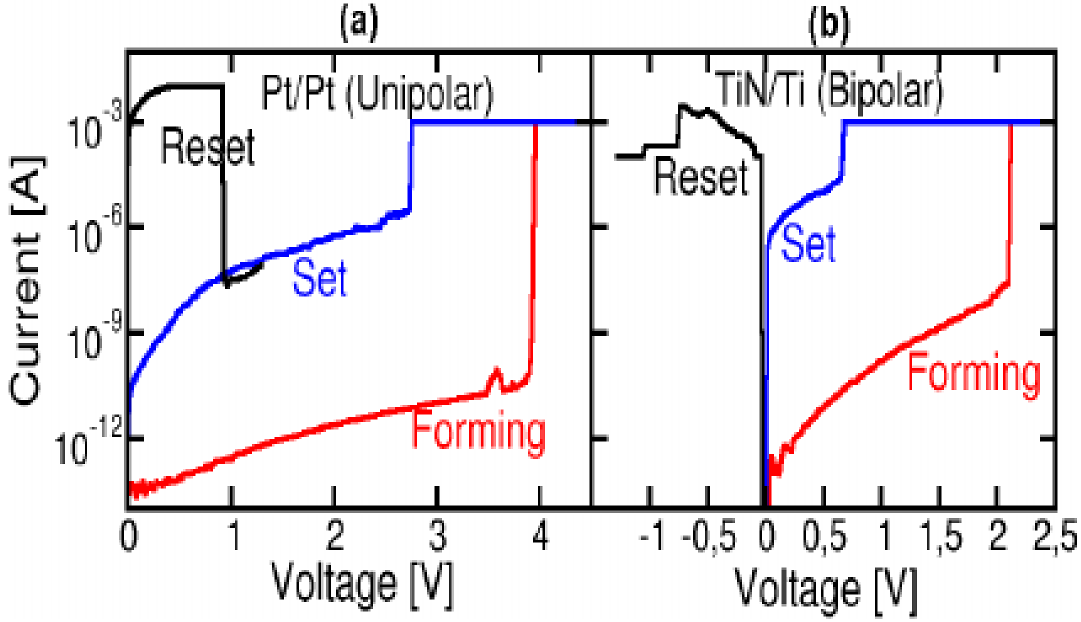
# Anion Switching




- Movement of oxygen vacancies ($HfO_x$, $TiO_x$, $TaO_x$ ...)
- Mostly bipolar

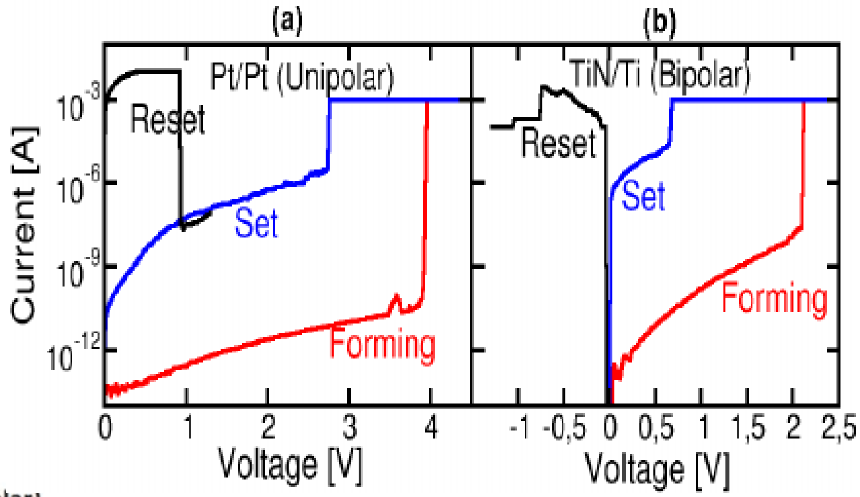
# Forming

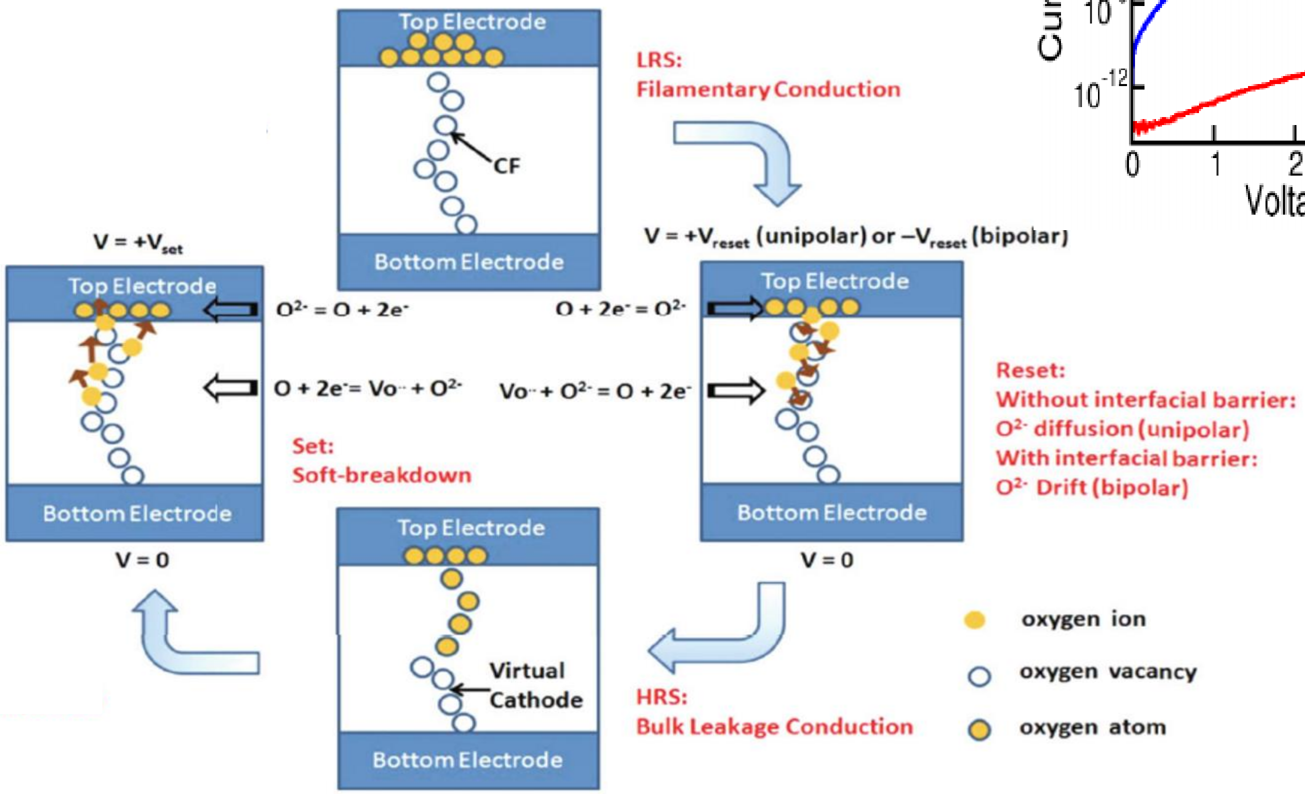



- First SET/soft breakdown process
- Requires higher voltage to form the filament pathway for the first time
- Current compliance is needed to prevent thermal runaway

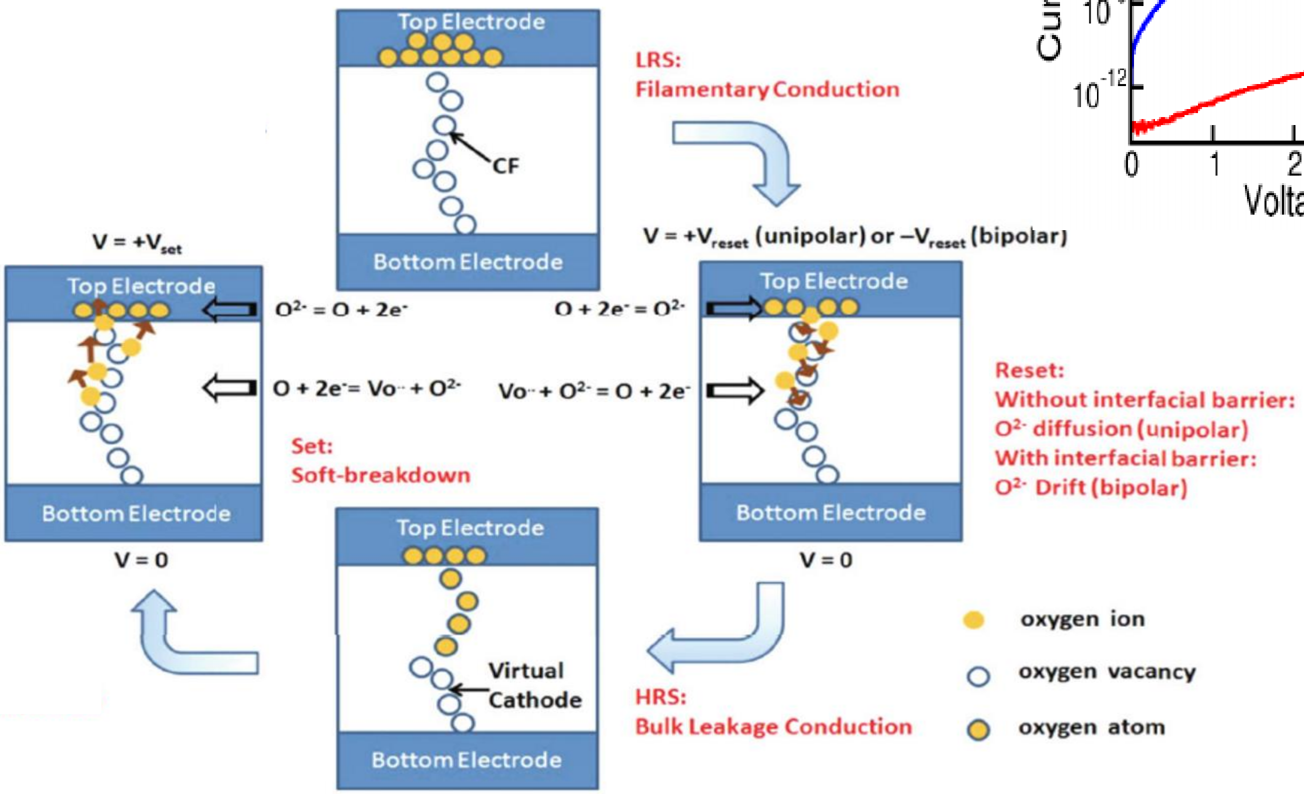
# SET

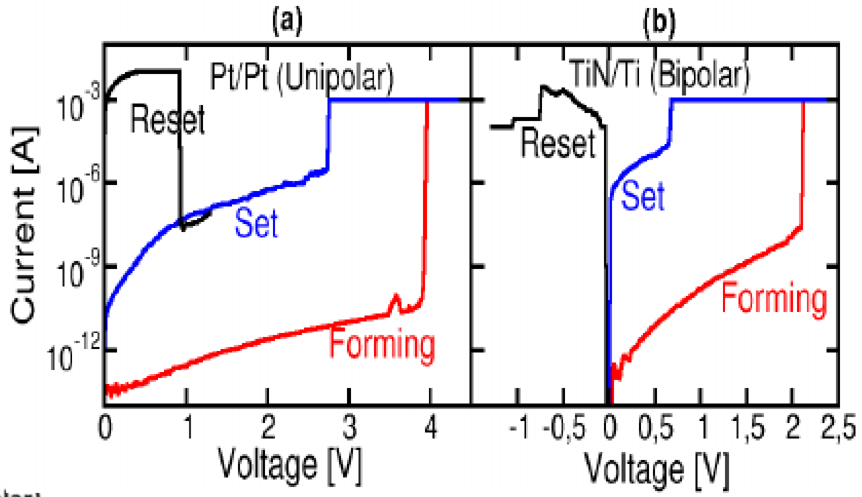



- E-field induced soft breakdown
- Conductive filament made of oxygen vacancy
- Abrupt SET

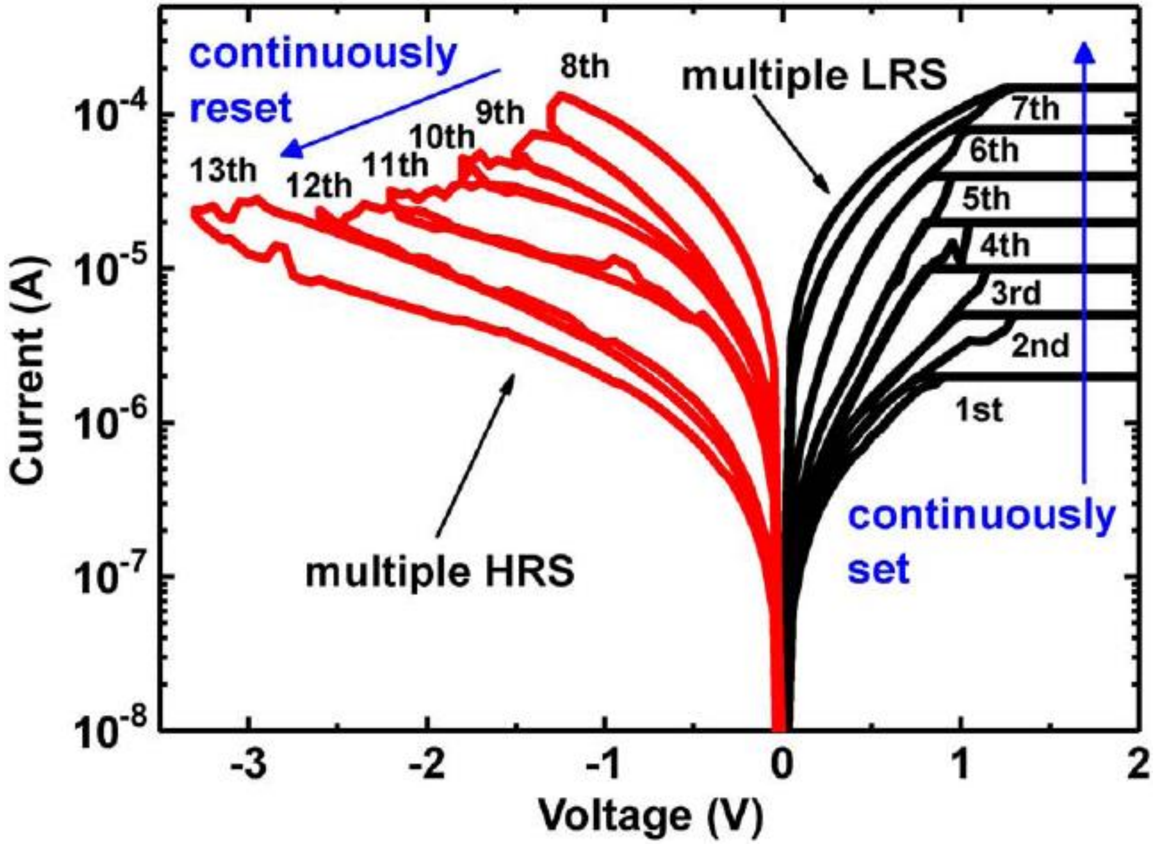
# RESET




- Gradual RESET
- Change of polarity for $O_2$ ions to move in the other direction
- Breaking of conductive filament

# Gradual SET Process




- Gradual SET for (top) $TiN/HfO_x/AlO_x/Pt$ (bottom)
- Possible reasons: multiple CF formed and/or stronger CF formed with larger diameter