# RRAM technology:
# From material physics to devices

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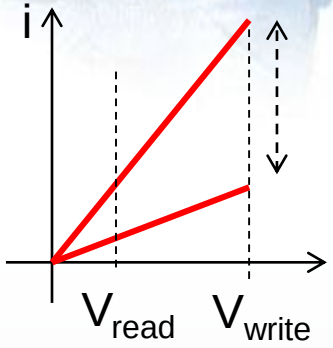
# Outline

- Introduction: RRAM technology and applications
- Few examples:
  - Ferroelectric tunnel junction memory
  - Mott Insulator memory
  - Electro Chemical Memory (CB-RAM)
  - OxRAM
    - Valence Change Memory
    - Thermo Chemical Memory
- Conclusion: main challenges

# RRAM: big picture

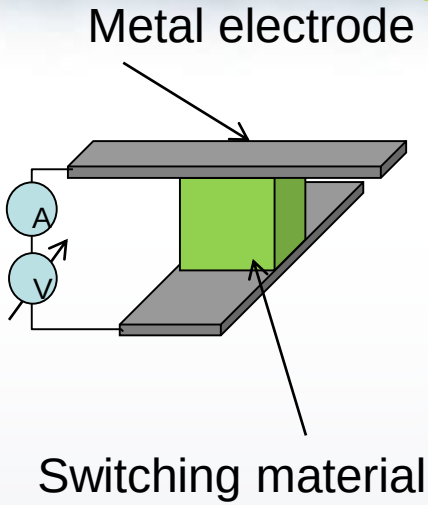
## Principle of RRAM




$R_{on}$= logical"1"

$R_{off}$= logical"0"

- Induce a change of resistivity to discriminate two (or more) resistance states by electrical stress (1 bit of information, or more)
- Evaluate this state by a "Read" voltage, i.e. probing current
- Equivalent to a tunable resistor
- Non volatile



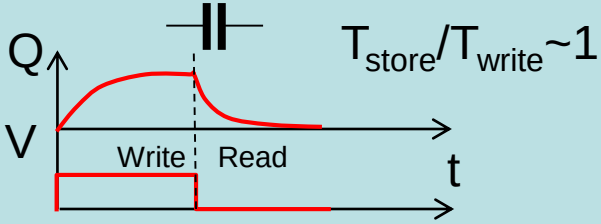

## The time voltage dilemma

In other words: we want the write voltage $V_{write}$ to be fast and to induce a large change of resistance and we want to be able to read for a very long time at $V_{read}$ w/o changing the state: not trivial.

Whatever is the physical mechanism originating the change of resistance, we need

**NON LINEARITY**

Ex: the worst non-volatile memory
Storing charge on a capacitor




$T_{store}/T_{write}$~1

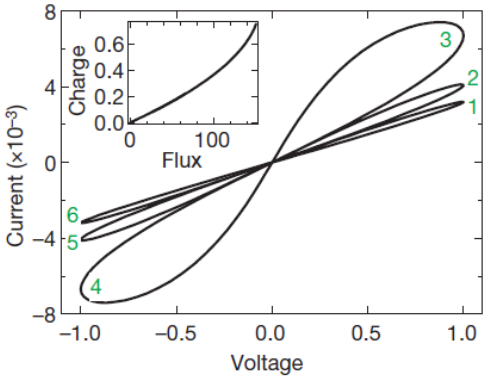

$T_{store}/T_{write}$>10^6 to become a Non-Volatile memory

# Some semantic…

There is today a debat around the proposition of memristance by HP in 2008.

$$v = \mathcal{R}(w)i$$

$$\frac{dw}{dt} = i$$




If we follow precisely the definition of memristor, none of the RRAM belongs to this class, but if we extend memrsitor to memristive devices, all RRAM can fit into this class…

“More or less the same, but not exactly similar…”

Classification under construction

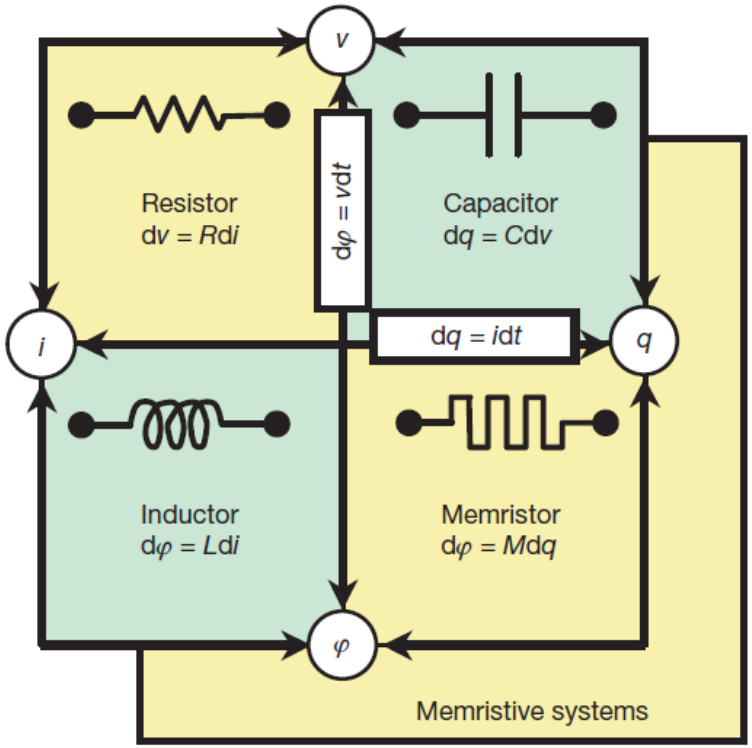
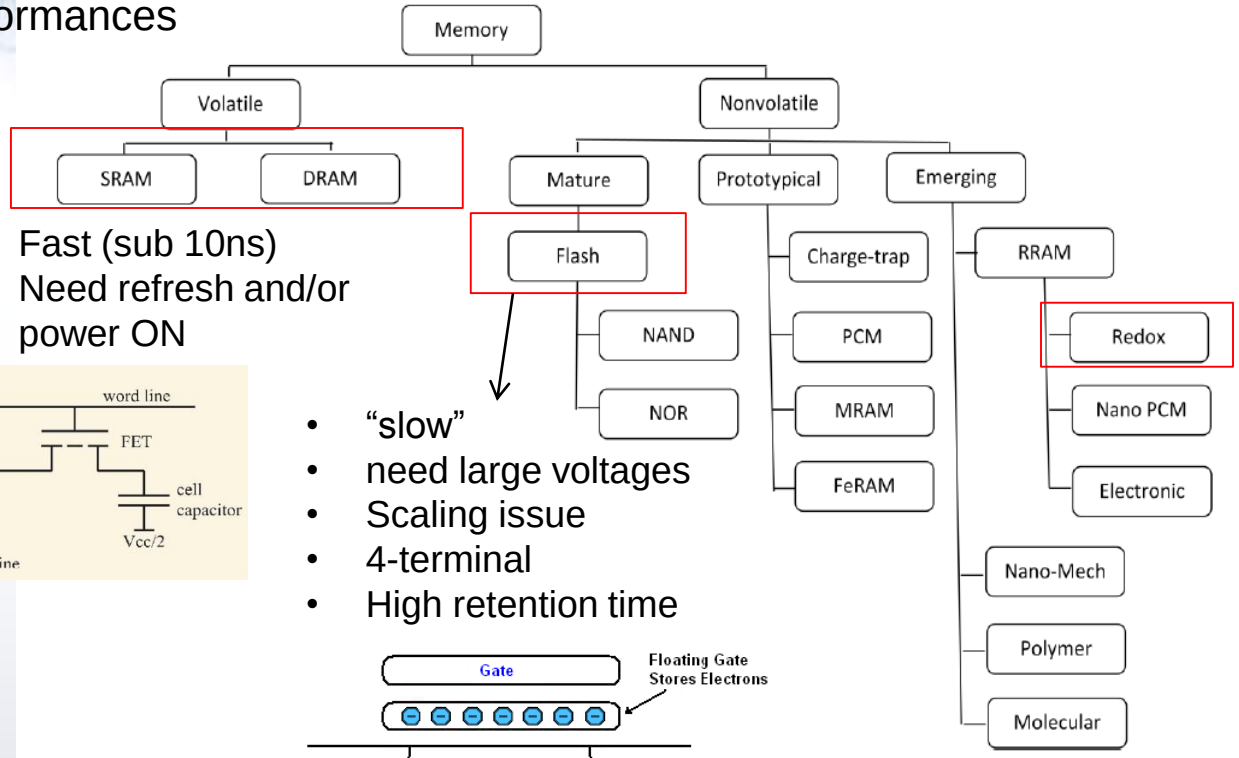



**Figure 1 | The four fundamental two-terminal circuit elements: resistor, capacitor, inductor and memristor.** Resistors and memristors are subsets of a more general class of dynamical devices, memristive systems. Note that $R$, $C$, $L$ and $M$ can be functions of the independent variable in their defining equations, yielding nonlinear elements. For example, a charge-controlled memristor is defined by a single-valued function $M(q)$.

# The Holy grale: a universal memory

For RRAM to become a success story, it needs to bring more to industry, not only equivalent performances

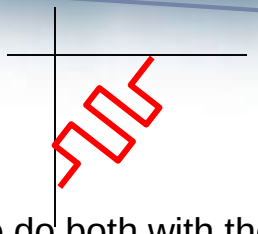



- Fast (sub 10ns)
- Need refresh and/or power ON




- "slow"
- need large voltages
- Scaling issue
- 4-terminal
- High retention time



Try to do both with the same device:

- Fast (<10ns)
- Low switching energy (pJ)
- Non-volatile (10 year@85C)
- Reliable
- High endurance (up to $10^{12}$ cycles

And more…

- Sub 10 nm integration
- New computing solution
- Multi-bit

**Table 1 | Comparison of memory and storage technologies[119]. Note that circuit-level overheads for the listed performance metrics are in general different among different device technologies and could often dominate individual device performance.***

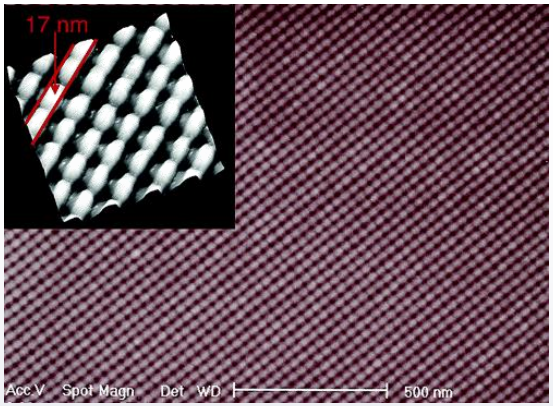
| | Memristor | PCM | STTRAM | SRAM | DRAM | Flash (NAND) | HDD |
|---|---|---|---|---|---|---|---|
| | | Prototypes | | Commercialized technologies | | | |
| Reciprocal density ($F^2$) | <4 | 4–16 | 20–60 | 140 | 6–12 | 1–4† | 2/3 |
| Energy per bit (pJ) | 0.1–3 | 2–25 | 0.1–2.5 | 0.0005 | 0.005 | 0.00002 | $1–10 \times 10^9$ |
| Read time (ns) | <10 | 10–50 | 10–35 | 0.1–0.3 | 10 | 100,000 | $5–8 \times 10^6$ |
| Write time (ns) | ~10 | 50–500 | 10–90 | 0.1–0.3 | 10 | 100,000 | $5–8 \times 10^6$ |
| Retention | years | years | years | As long as voltage applied | <<second | years | years |
| Endurance (cycles) | $10^{12}$ | $10^9$ | $10^{15}$ | $>10^{16}$ | $>10^{16}$ | $10^4$ | $10^4$ |

*The energy to operate NAND Flash is typically hundreds of picojoules per bit primarily because accessing the memory cells requires charging word and bit lines to high voltages. †Smaller number represents an effective area for multi-level cells. PCM, phase-change memory; STTRAM, spin torque transfer random access memory; SRAM, static RAM; DRAM, dynamic RAM; HDD, hard disk drive.

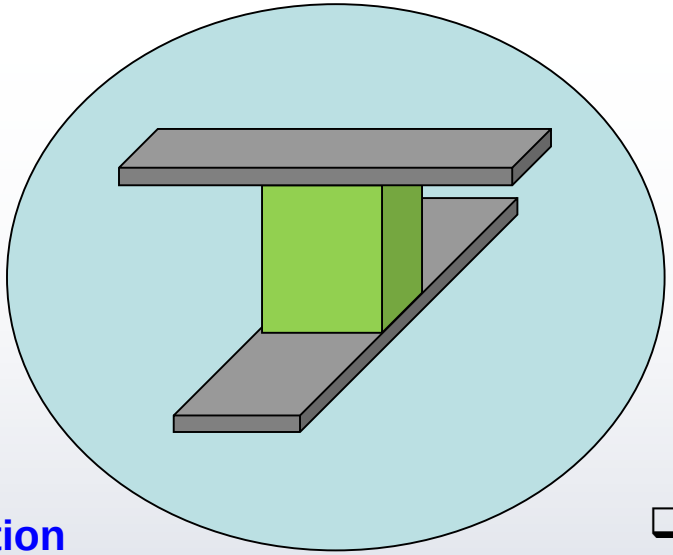
# RRAM potential

## PROS and CONS

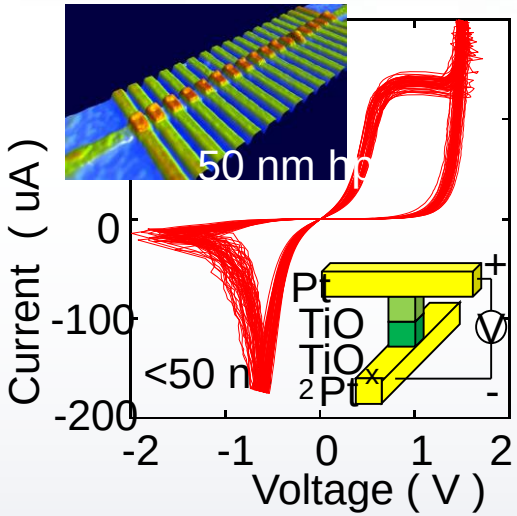
- **Wide range of material systems (many CMOS compatible) and physical phenomena**
- **High density due to lateral scaling and ..**




HPLab, 2005



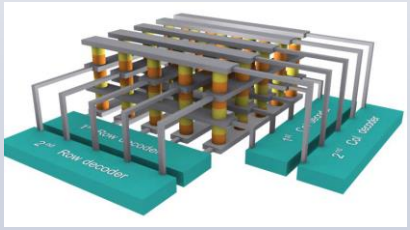
- **but simple functionality**



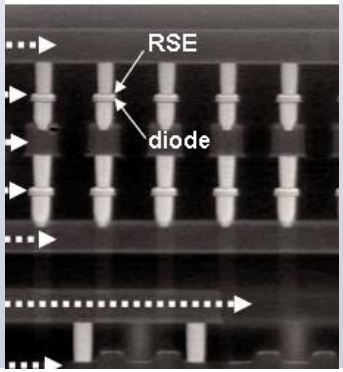

J. Yang *et al. Nature Nano,* (2008)

- **Solution: hybrid circuits**

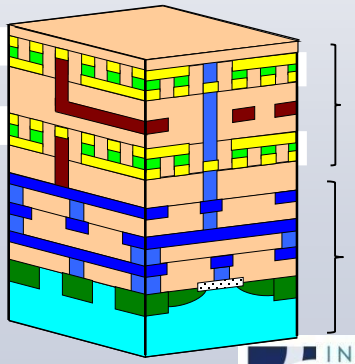
**… monolithical 3D integration**



M.-J.Lee et al. *IEDM* 85 (2008)



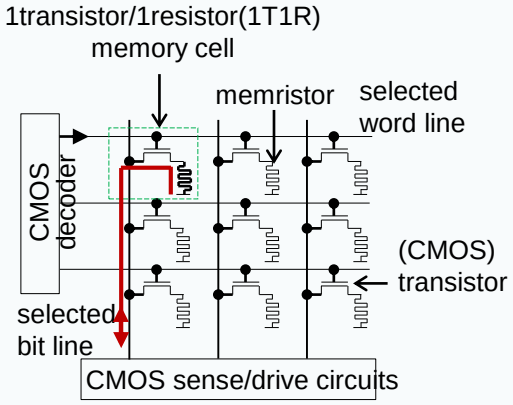

Kawahara et al. Samsung, 2012

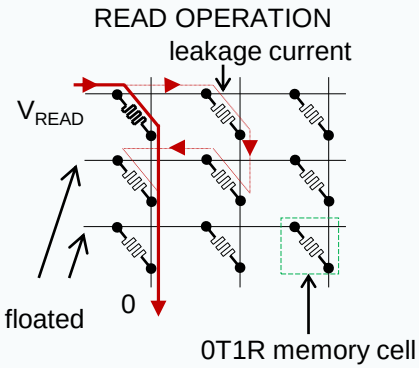


crossbar add-on with integrated memristive devices
CMOS circuits

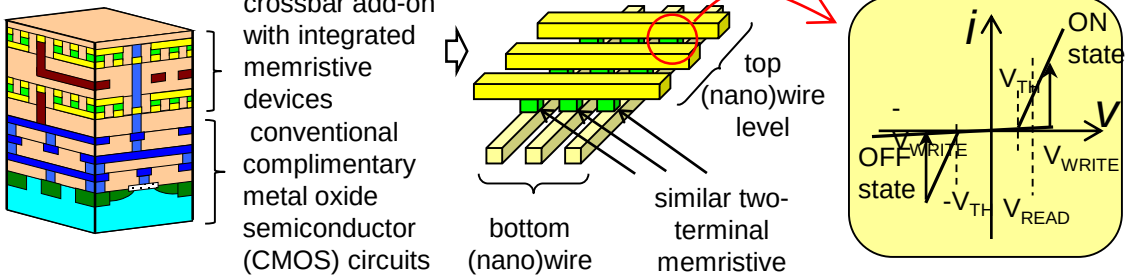
# Killer Applications

## MEMORIES AND STORAGE

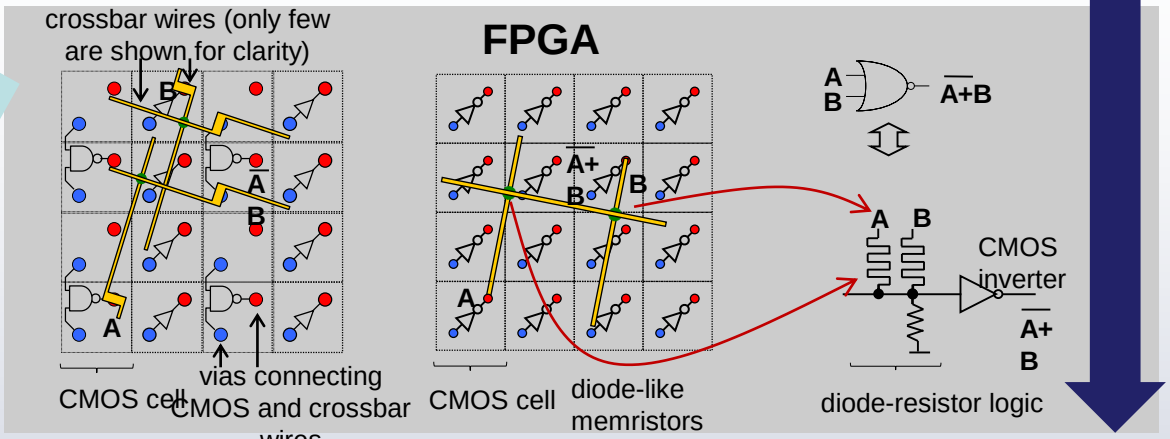


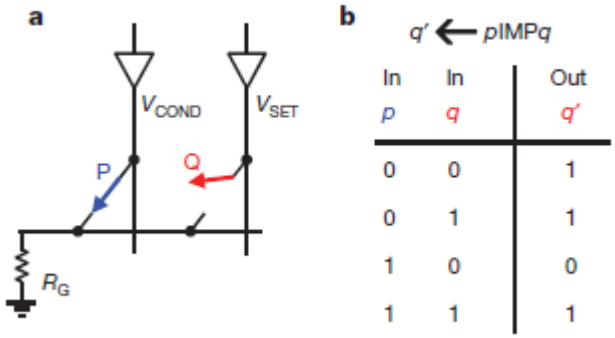

## HYBRID CIRCUITS



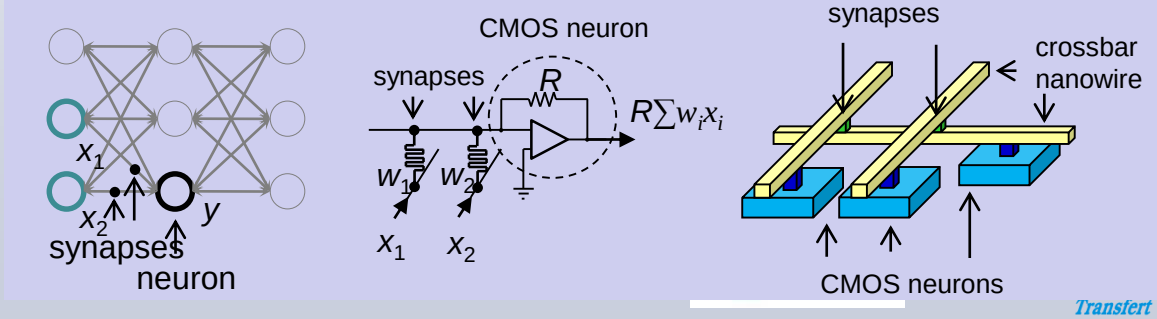

## FPGA



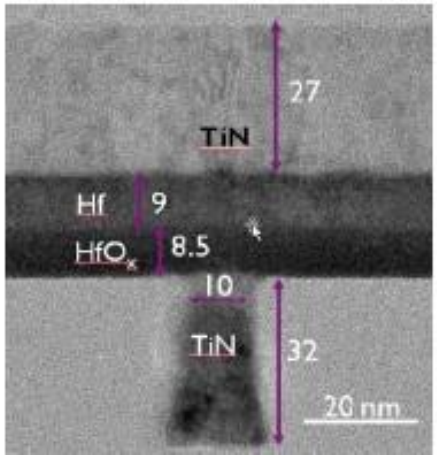

## LOGIC
## (HPLab, Nature)



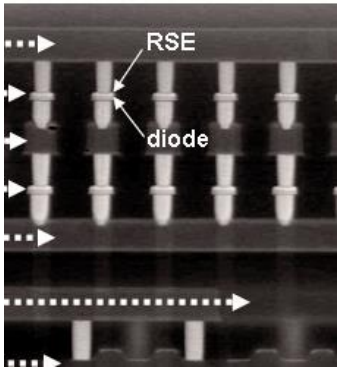

## BIO-INSPIRED AND MIXED-SIGNAL INFORMATION PROCESSING



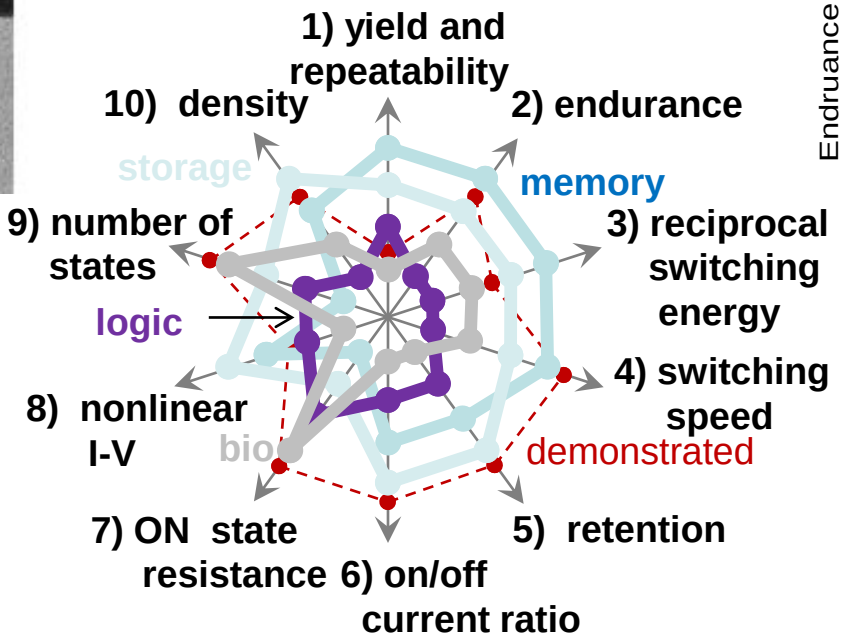
# State-of-the-Art Performance



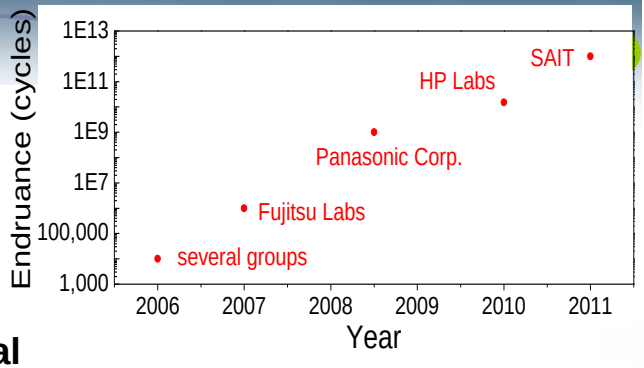

Govoreanu,et all IEDM, 2012

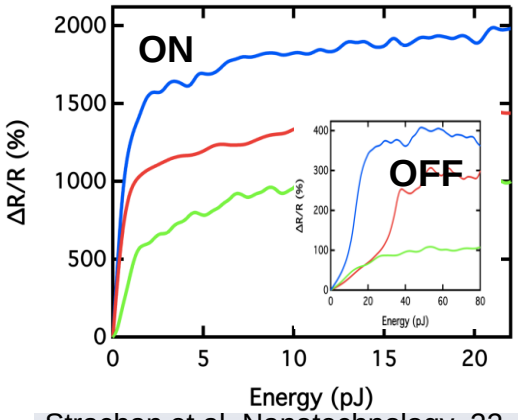



Kawahara et al. Samsung, 2012

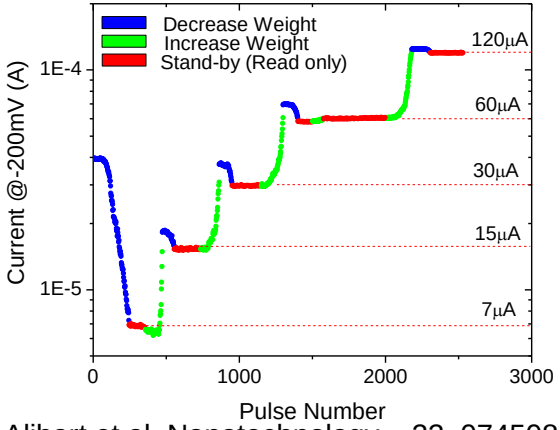



J. Yang and D. Strukov (Nature Nano 2013)

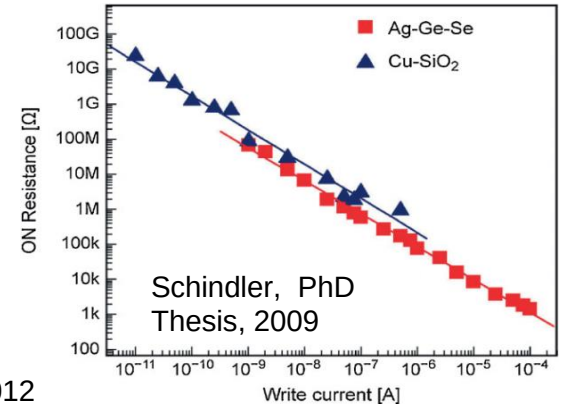


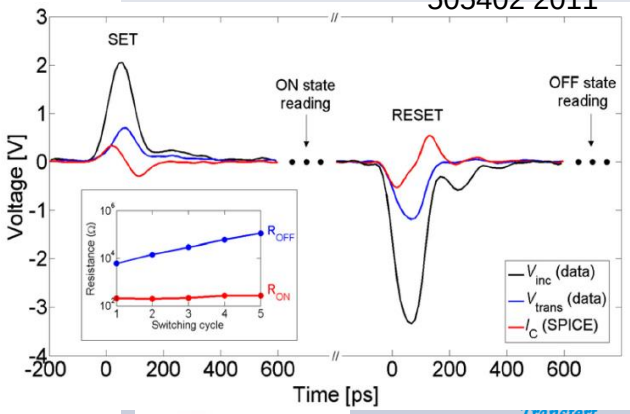




Strachan et al, Nanotechnology, 22, 505402 2011

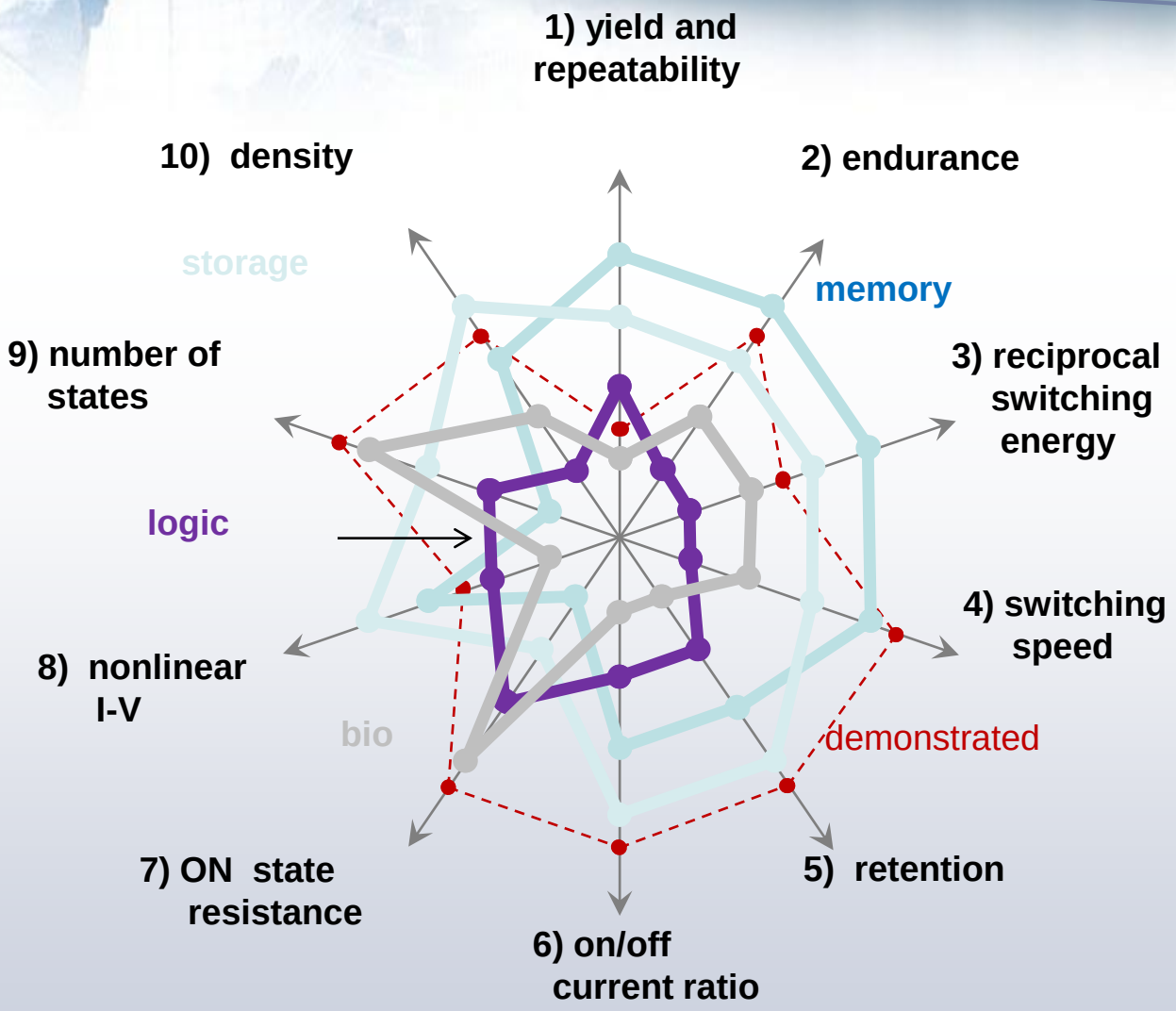



Alibart et al, Nanotechnology , 23, 074508, 2012



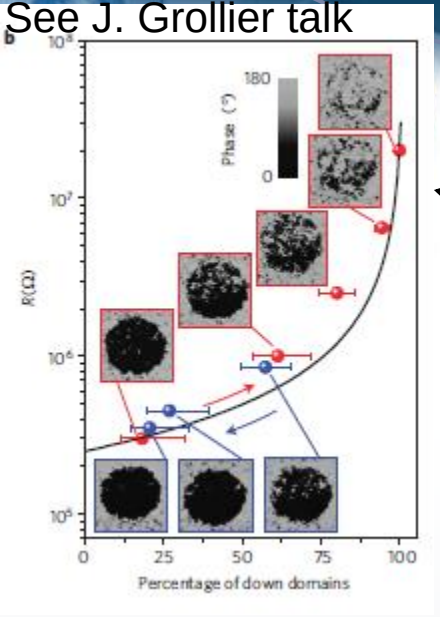




Torrezan et al, Nanotechnology, 22, 485203 2011


1) yield and repeatability
2) endurance
3) reciprocal switching energy
4) switching speed
5) retention
6) on/off current ratio
7) ON state resistance
8) nonlinear I-V
9) number of states
10) density
storage
memory
logic
bio
demonstrated

# RRAM technologies

See J. Grollier talk



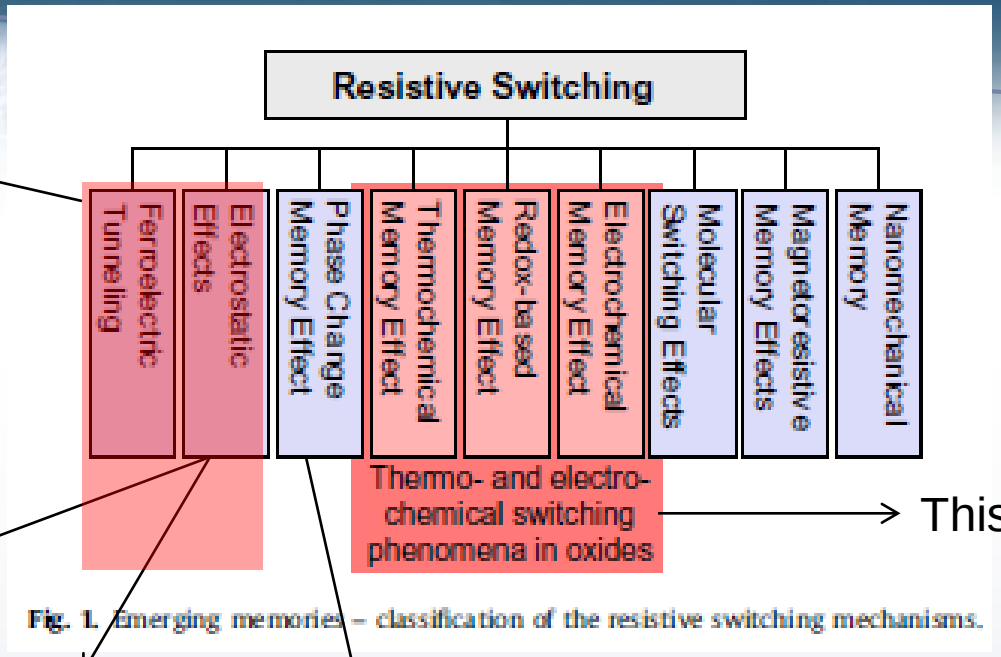
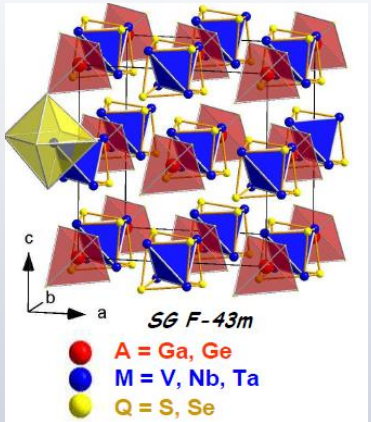
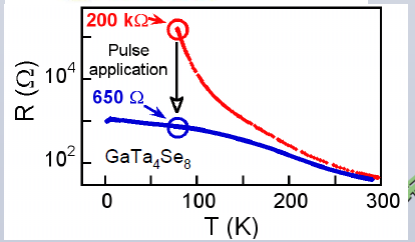



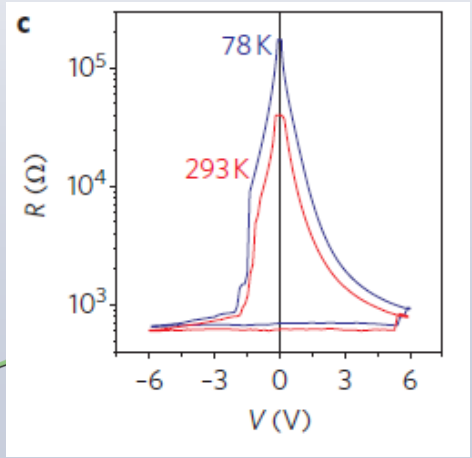

Fig. 1. Emerging memories – classification of the resistive switching mechanisms.

Mott transition
See J. Tranchant (IMN) talk

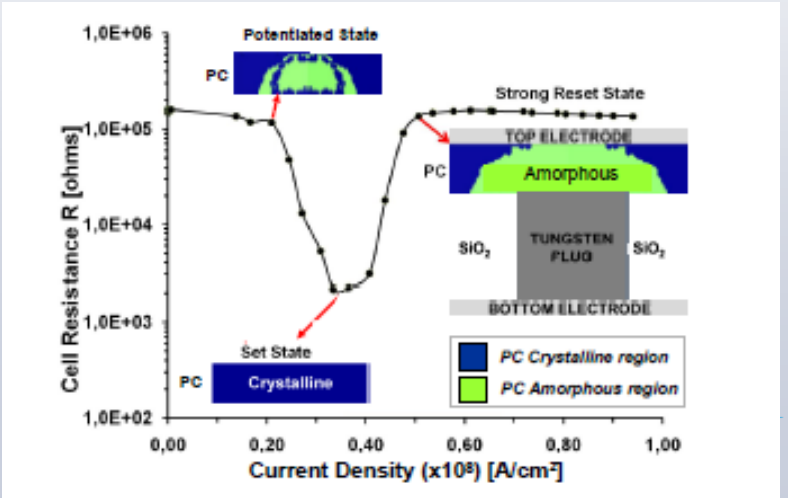



Chen-NatNano2012
Anderson localisation tunning in SiO2_Pt/NPs films



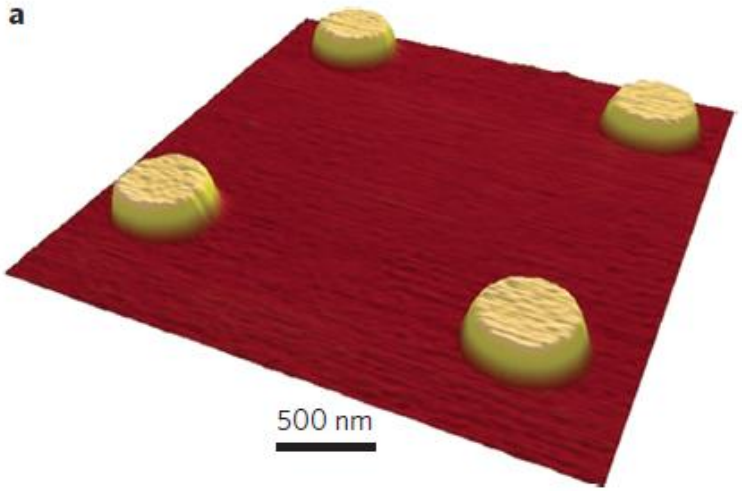

Thermally-induced phase change

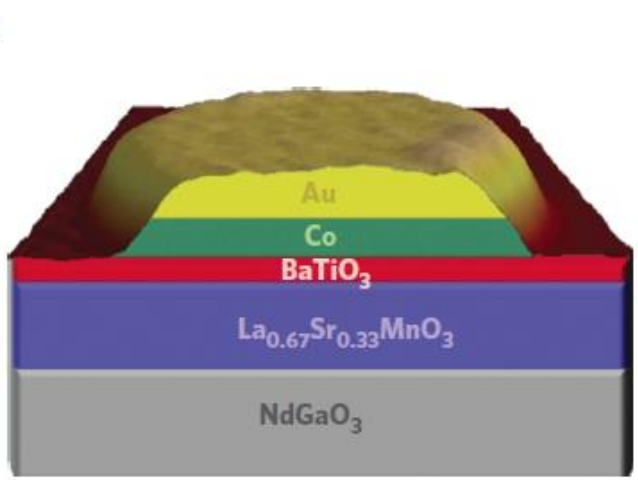


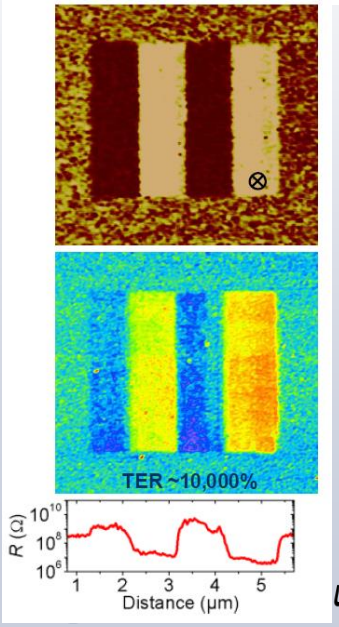
# FeRAM

Work from UMPhys-Thales (Paris)

Change of resistivity is associated to the change of polarization of a ferroelectric thin film

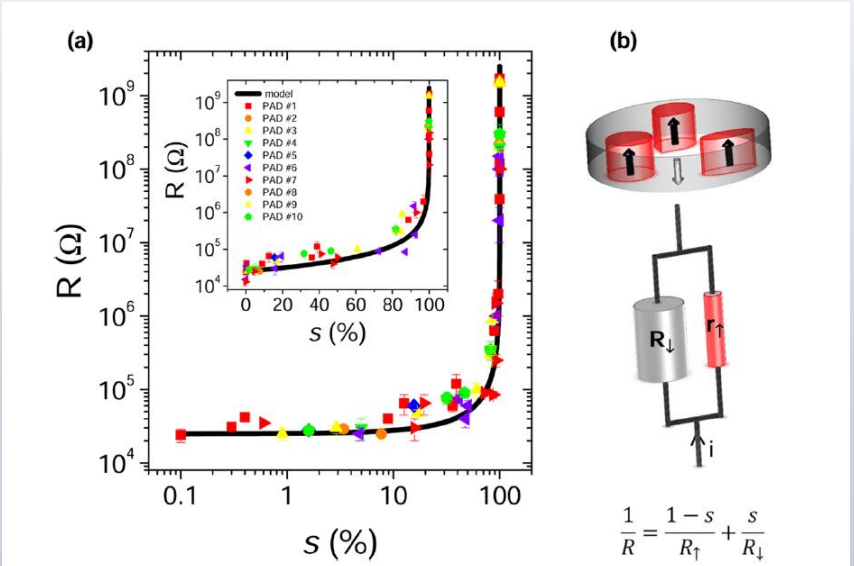



PFM analysis of domains reversal via electric field stress

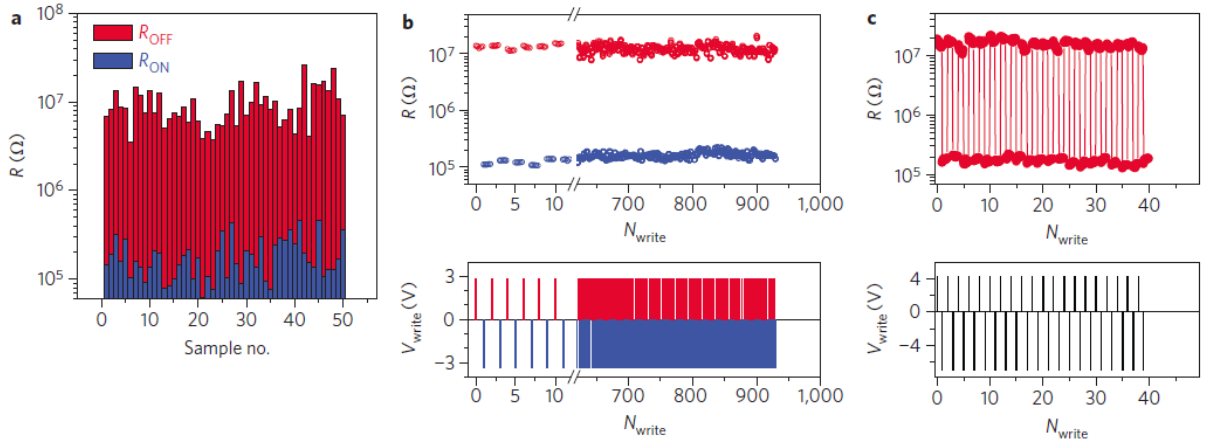
Polarization -> change of band alignment -> change of resitivity

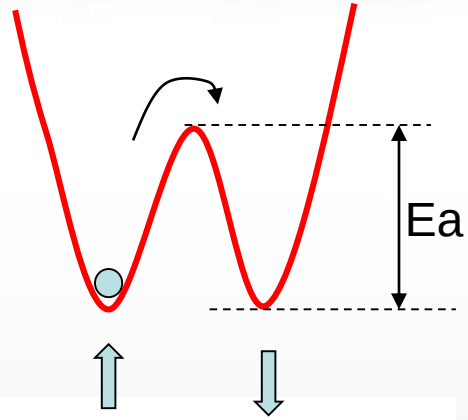


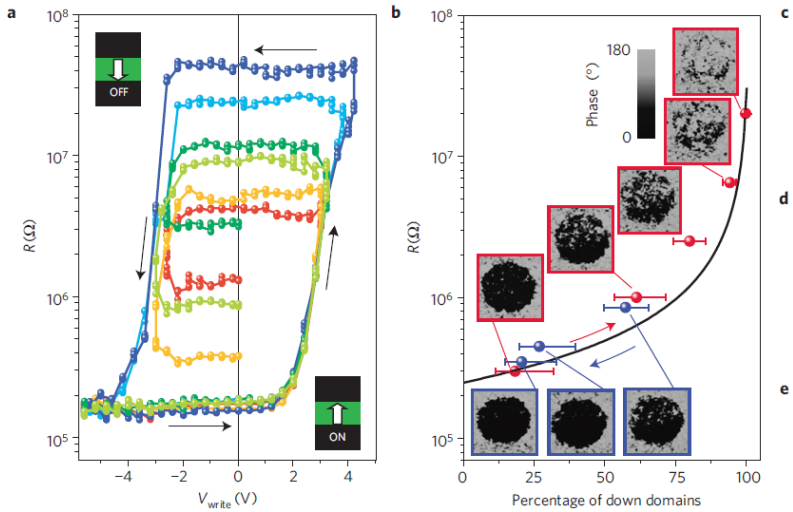
# FeRAM

Non-linearity:

Exp(Ea/kT) >< Exp(qV/kT)



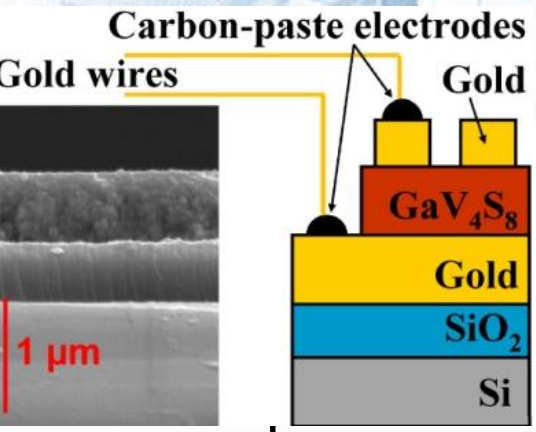

| | Volatile | | Non-volatile | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DRAM | SRAM | NAND Flash | Trapping charge | FeRAM | MRAM | PCM | FTRAM |
| Storage mechanism | Charge on capacitor | Interlocked state of logic gates | Charge on floating gate | Charge trapped in gate insulator | Ferroelectric polarization | Magne-tization | Amorphous/ cristalline phases | Ferroelectric polarization |
| Cell elements | 1T1C | 6T | 1T | 1T | 1T1C | 1(2)T1C | 1T1R | 1T1R |
| Feature size (nm) | 50 | 65 | 90 | 50 | 180 | 130 | 65 | 50 |
| Cell area | $6F^2$ | $140F^2$ | $5F^2$ | $6F^2$ | $22F^2$ | $45F^2$ | $16F^2$ | $4F^2$ |
| W/E time | <10 ns | 0.3 ns | 0.1 ms | 20 μs | 10 ns | 20 ns | 50 ns | 10 ns |
| Retention time | 64 ms | 0 | > 10 y | > 10 y | > 10 y | >10 y | >10 y | > 5 days |
| Write cycles | >1E16 | >1E16 | >1E5 | >1E5 | 1.00E+14 | >1E16 | 1.00E+09 | >900 |
| Write voltage | 2.5 | 2.5 | 15 | 8 | 0.9-3.3 | 1.5 | 3 | 3 |
| Read voltage | 1.8 | 1 | 2 | 1.6 | 0.9-3.3 | 1.5 | 3 | 0.1-1 |
| Write energy | 5 fJ | 0.7 fJ | 10 fJ | 100 fJ | 30 fJ | 100 pJ | 6 pJ | <10fJ |

Next big challenge:

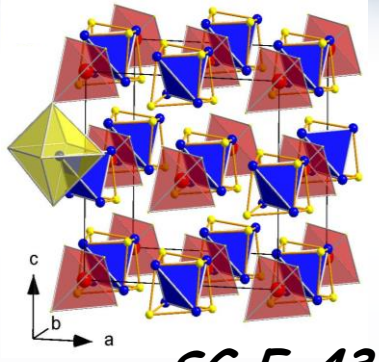
- Integration with CMOS friendly materials

# Mott Memory

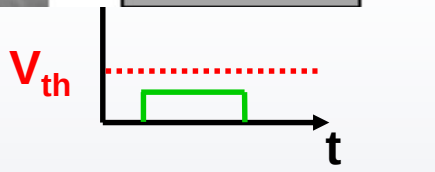
Work from IMN, Nantes

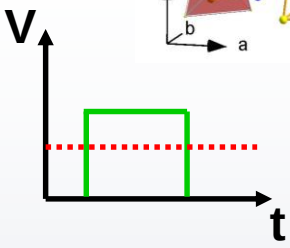


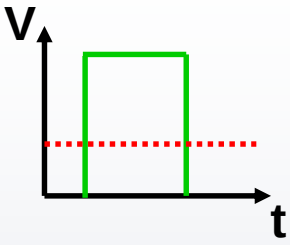

**Clustered lacunar spinel structure :**

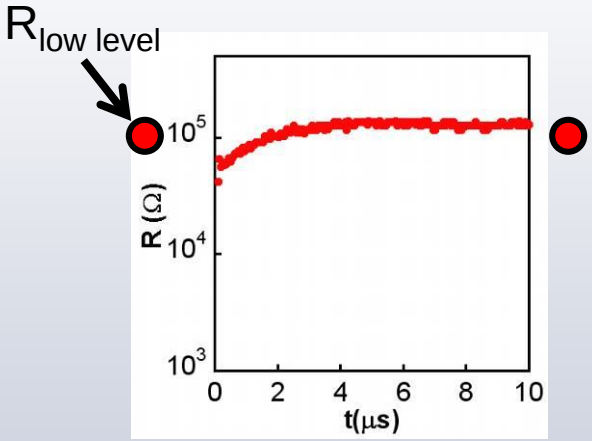


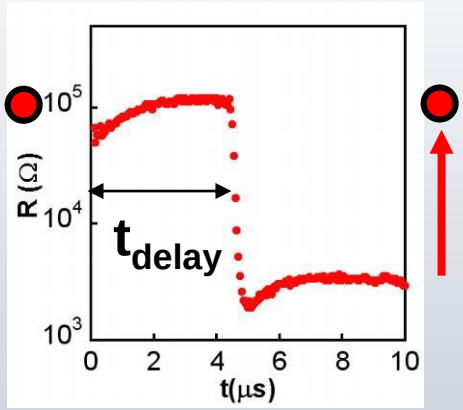

*SG F-43m*

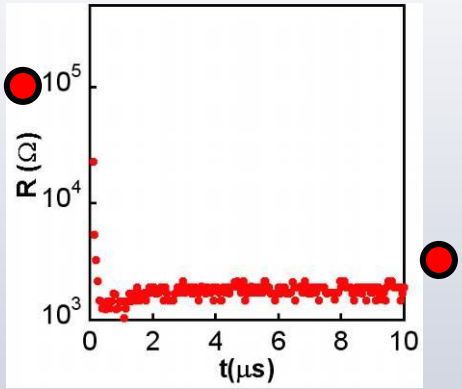


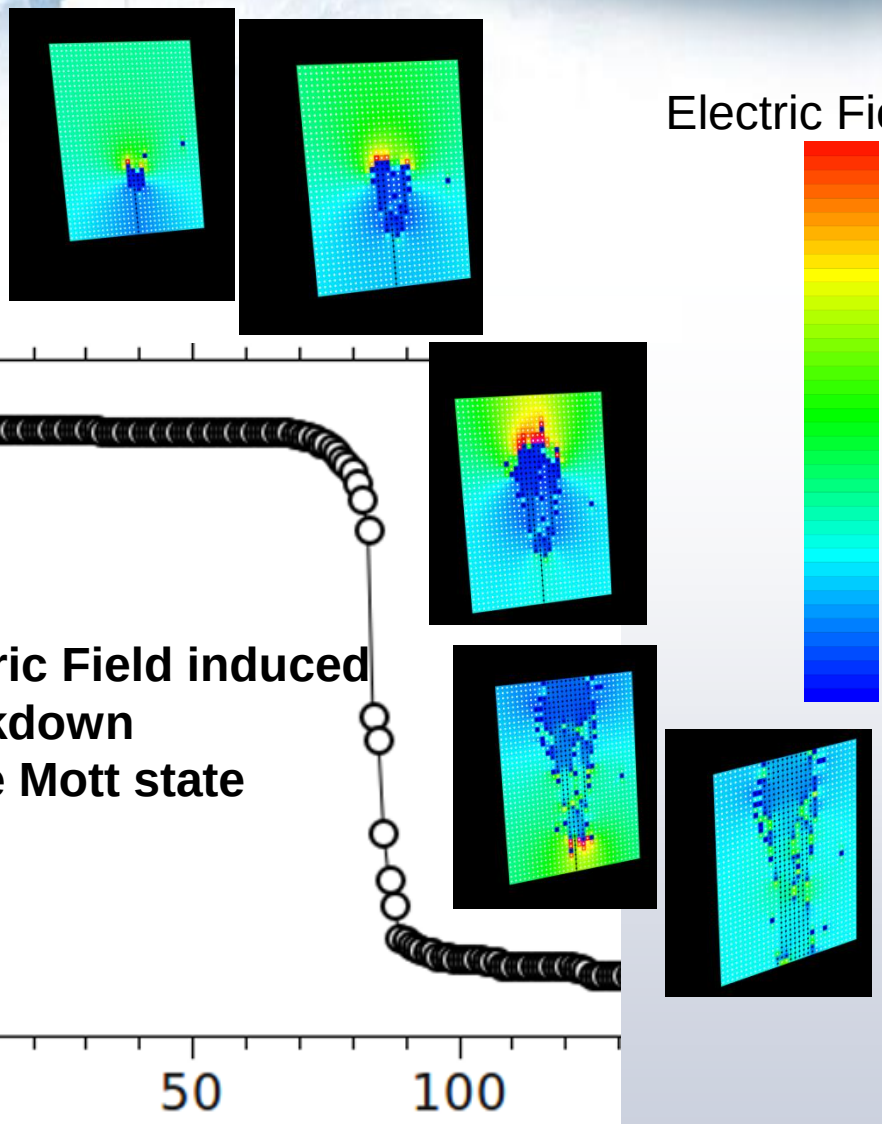

✓ no transition

✓ volatile
Resistive switching

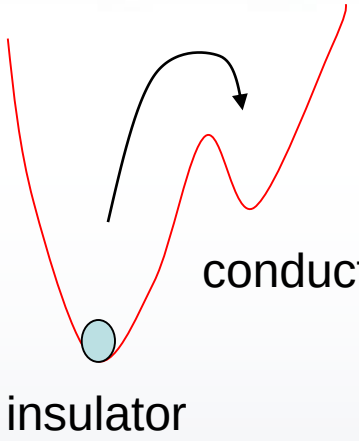
✓ fast non-volatile
Resistive switching

# Modeling of the volatile resistive switching

## Model




P. Stoliar *et al.*,
Adv. Mater. **25**, 3222 (2013)



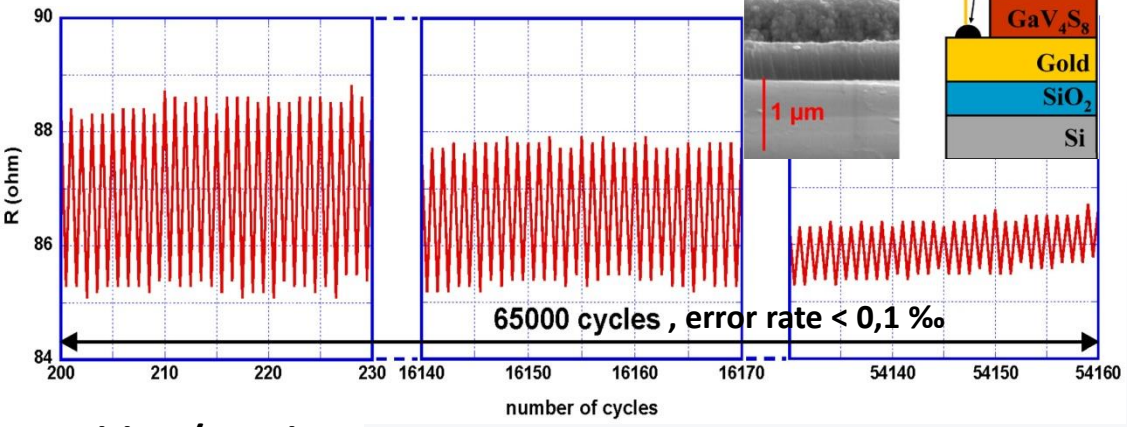

Metastable ON state
-> OFF state more stable
(volatile transition)
BUT domain size effect
that induces a non-
volatile transition

V. Guiot *et al.*
*Nature Comm.* **4**, 1722 (2013)

# Electrical performances of $GaV_4S_8$ for Mott memories

## Resistive switch cycling endurance

**2V / 1ms pulses** on 50x50µm² MIM structures



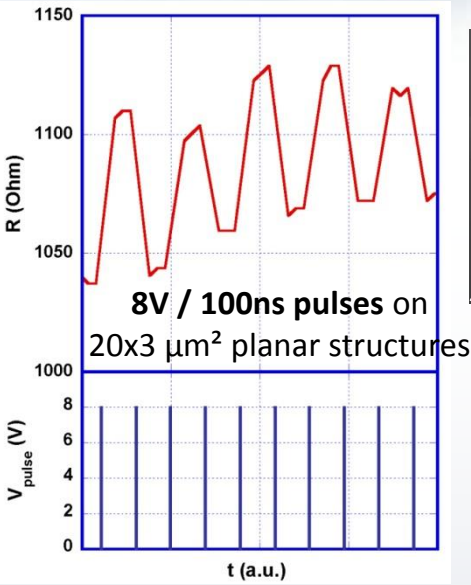




**+ writing / erasing voltage ≤ 2V**

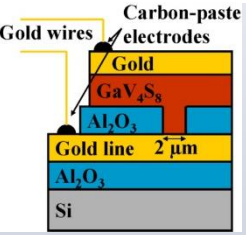
J. Tranchant et al. Thin Solid Films, 533 (2013) 61

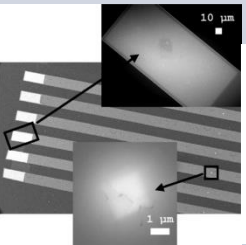
## Writing / erasing times ≤ 100 ns

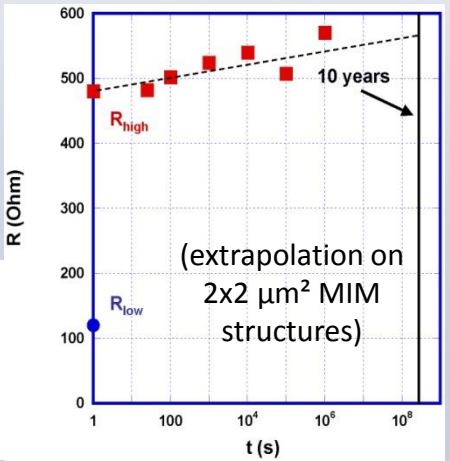


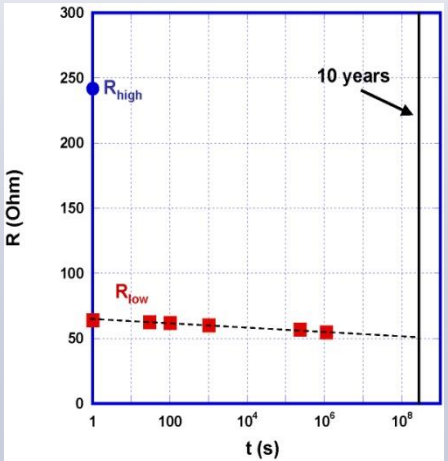


## Data retention : high and low resistance states > 10 years

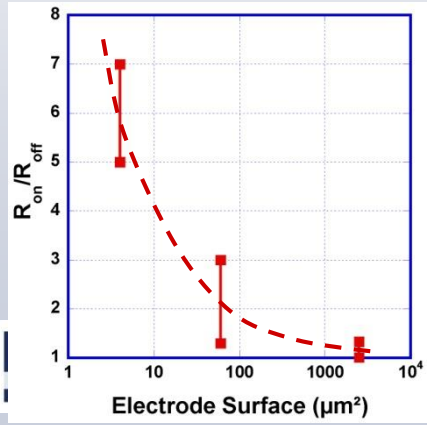





## Increase of $R_{on}/R_{off}$ with downscaling



# Electrochemical Cell

- Other names:
  - Solid state electrolyte memory
  - Conductive bridge memory
  - Programmable metallization cell


Active Electrode
(e.g., Ag, Cu)

Solid state electrolyte with host ions $M^{Z+}$ ions
(e.g. $Ag_2S$, $Cu_2S$, $RbAg_4I_5$)
or
insulator doped with $M^{Z+}$
(e.g. $SiO_2$, $WO_2$, GeS, GeSe)

typically amorphous or crystalline

Counter Electrode
(e.g., Pt, Ir, Au, W)

| Electrolytes | Bottom Electrode | Top electrode | Switching mode | reference |
|---|---|---|---|---|
| **Sulfides:** | | | | |
| $Ge_xS_x$ | W | Ag | Bipolar | 55 |
| $As_2S_3$ | Au | Ag | Bipolar | 56 |
| $Cu_2S$ | Cu | Pt | Bipolar | 57, 58 |
| $Zn_xCd_{1-x}S$ | Pt | Ag | Bipolar | 59 |
| **Iodides:** | | | | |
| AgI | Pt | Ag | Bipolar | 60 |
| $RbAg_4I_5$ | Pt | Ag | Bipolar | 61 |
| **Selenides:** | | | | |
| $Ge_xSe_y$ | W | Ag, Cu | Bipolar | 62 |
| **Tellurides:** | | | | |
| $Ge_xTe_y$ | TiW | Ag | Bipolar | 63 |
| **Ternary chalcogenides:** | | | | |
| Ge-Sb-Te | Mo | Au, Ag | Bipolar | 64 |
| **oxides** | | | | |
| $Ta_2O_5$ | Pt | Cu | Bipolar | 65 |
| $SiO_2$ | W | Cu | Uni/Bipolar | 66 |
| $HfO_2$ | Pt | Cu | Bipolar | 67 |
| $WO_3$ | Pt | Cu | Bipolar | 68 |
| $ZrO_2$ | Ag | Au | Bipolar | 69 |
| $SrTiO_3$ | Pt | Ag | Bipolar | 70 |
| $TiO_2$ | Pt | Ag | Bipolar | 71 |
| $CuO_x$ | Cu | Al | Unipolar | 72 |
| ZnO | Pt, Al doped ZnO | Cu | Bipolar | 73 |
| $Al_2O_3$ | Al | Cu | Bipolar | 74 |
| MoOx | Cu | Pt | Bipolar | 75 |
| $GdO_x$ | Pt | Cu doped $MoO_x$ | | 76 |
| **Others:** | | | | |
| MSQ | Pt | Ag | Bipolar | 77 |
| doped organic semiconductors | Pt | Cu | Bipolar | 78 |
| nitrides | Pt | Cu | Bipolar | 79 |
| amorphous Si | $P^+$-Si | Ag | Bipolar | 80 |
| Carbon | Pt | Cu | Bipolar | 81 |
| vacuum gaps | $RbAg_4I_5$/Ag, $Ag_2S$/Ag | W, Pt | Bipolar | 82, 83 |

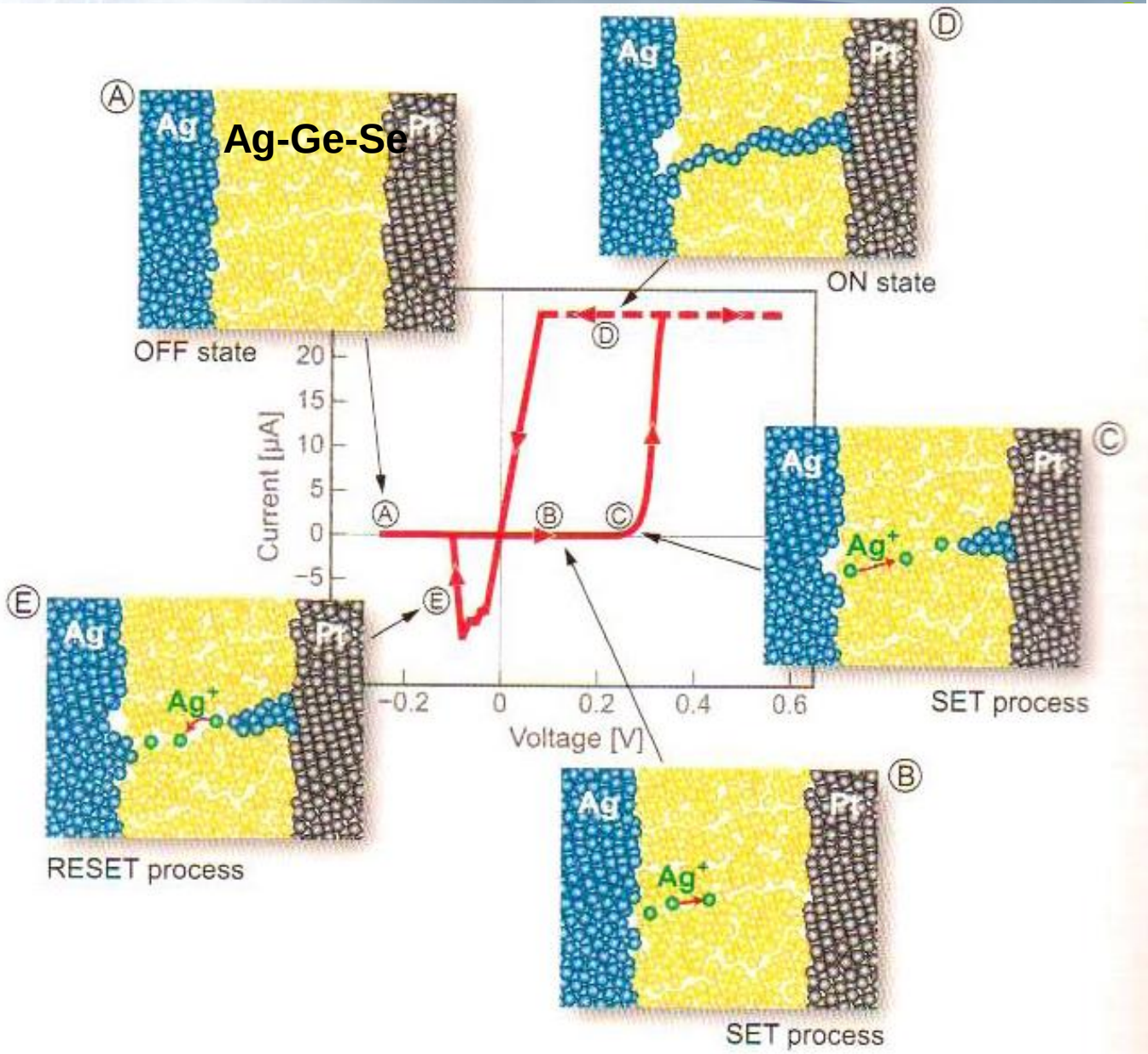
# Typical I-V and Process Cartoon

(A) OFF state

(B, C) SET process: (i) Ag oxidized to $Ag^+$ ; (ii) drift in electric field ; (iii) reduced and electro-crystallized

(D) SET process: complete bridging (compliance-related)

(E) RESET process: opposite of SET (heat assisted?)



# SET Process

(a) Anodic oxidation and dissolution of M:

$M \rightarrow M^{z+}+ze^-$

(b) Migration of $M^{z+}$ across thin film (migrations is strongly enhanced by extended defects)

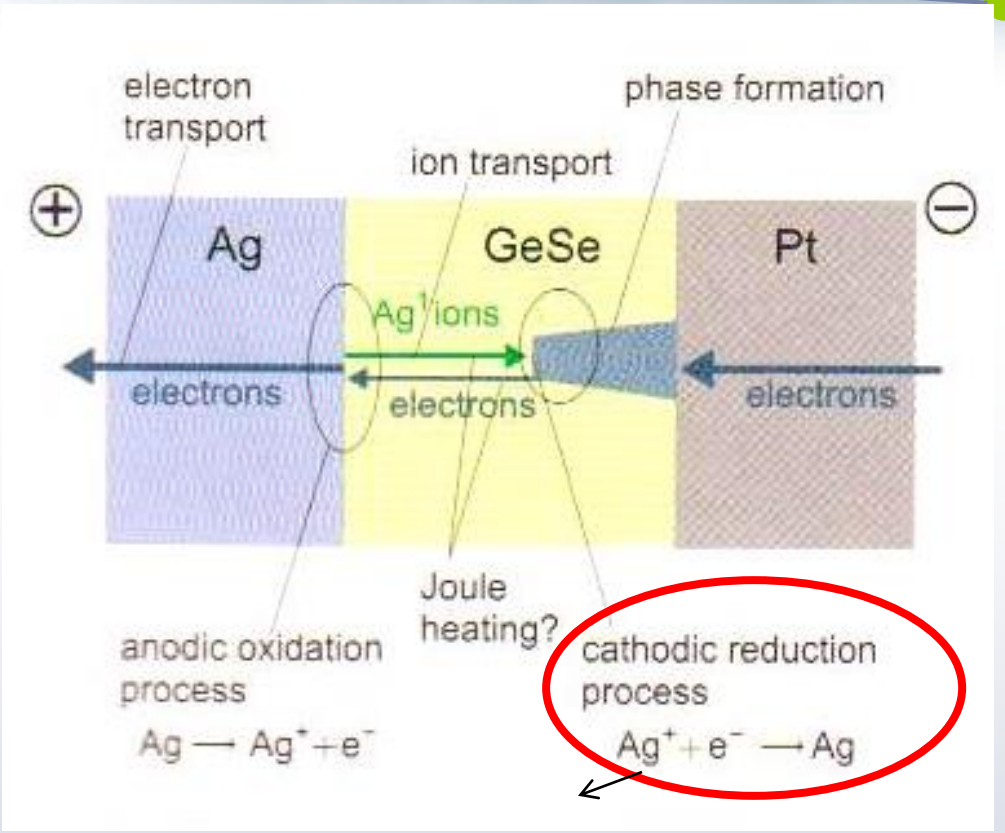
(c) Reduction and electro-crystallization of M on the surface of CE:

$M^{z+}+ze^- \rightarrow M$

→ Formation of filament growing (typically) in the direction of the active electrode.

→ A forming step (first sweep) is required

→ The growth is limited by current compliance




**Origin of Non-linearity**

Butler-Volmer equation for oxidation reductions

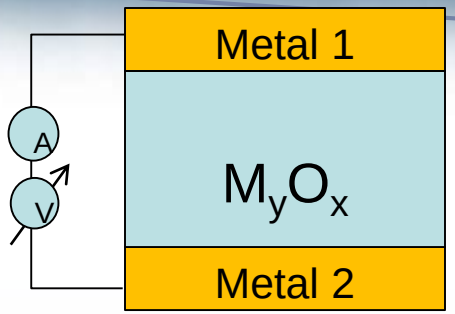
– Exponential for high overpotentials

Δφ~applied potential
α: cathodic charge transfer coef.

$$J = J_0\left[\exp\left(\frac{(1-\alpha)ze}{k_BT}\Delta\phi\right) - \exp\left(-\frac{\alpha ze}{k_BT}\Delta\phi\right)\right]$$

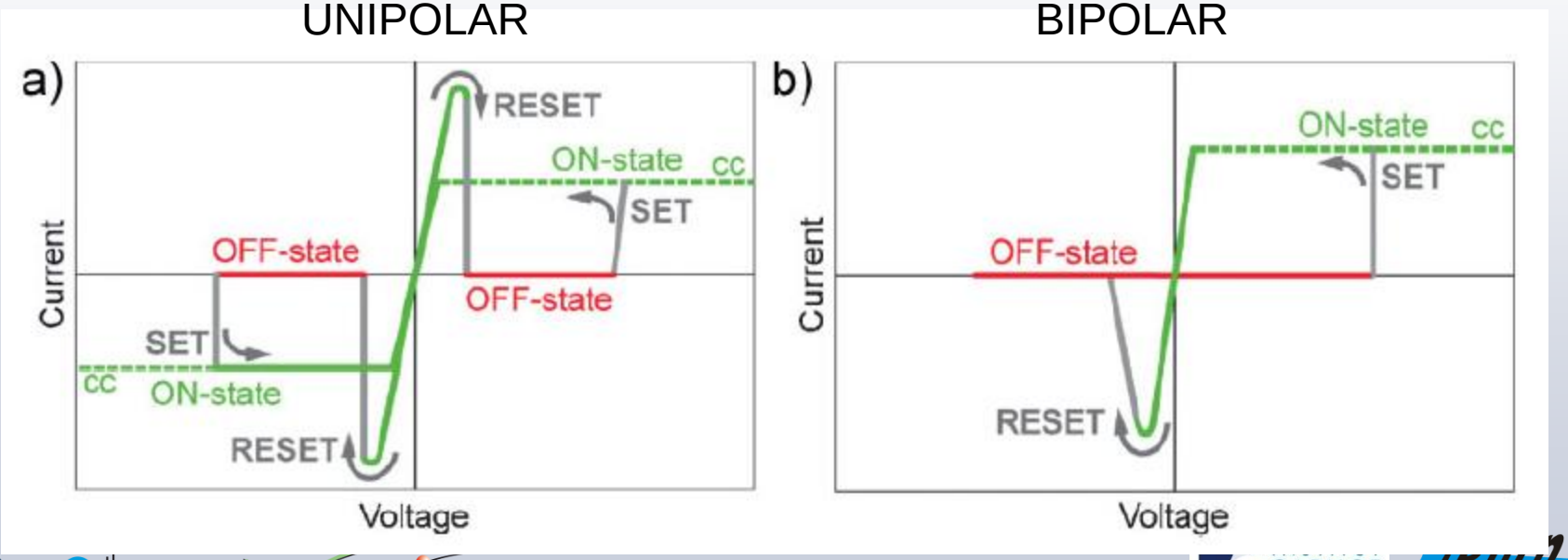
# Ox(ide)RAM (redox based)

OxRAM is typically a transition metal oxide sandwiched between inert electrodes
(no metal cations available as in ECM).
If a sufficient voltage (or current) stress is applied, the insulating material can become conductive
Two distinct I-V switching phenomena are reported
Unipolar: The same polarity can tune ON and OFF the cell
Bipolar: One polarity switch ON, the other switch OFF




"Thermo Chemical Memory"
UNIPOLAR

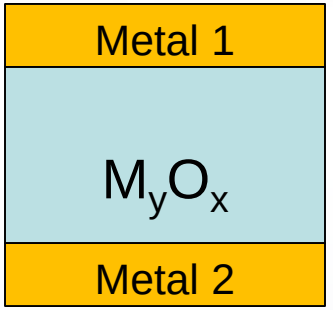
"Valence Change Memory"
BIPOLAR




What is happening?

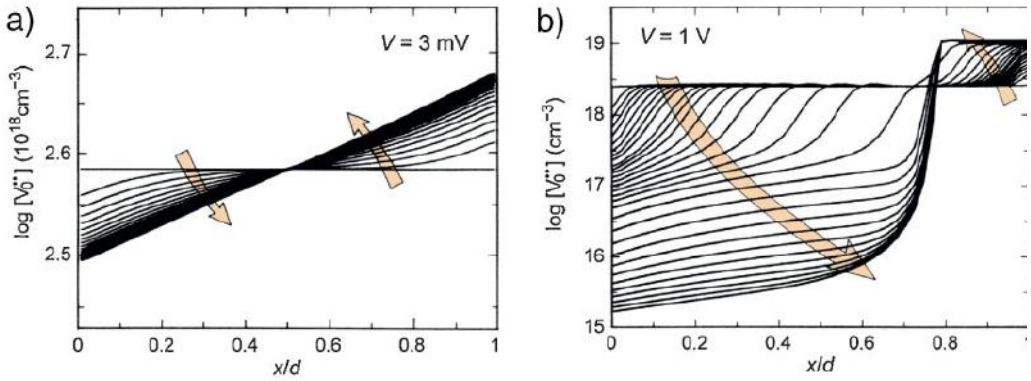
# Valence Change Memory (redox-based)

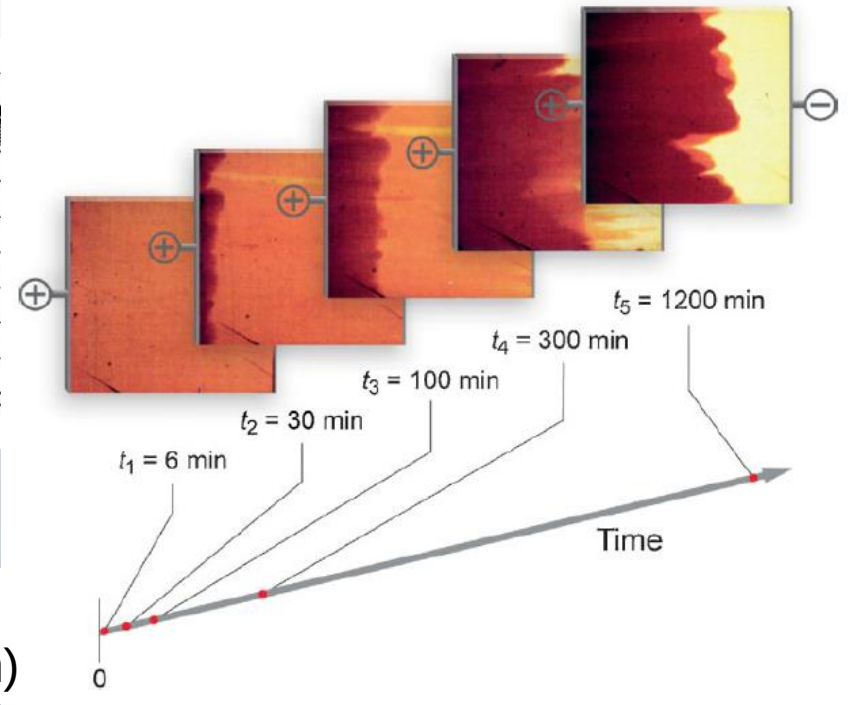
In TMO, oxygen vacancies ($V_O^{2+}$)are much more mobile than cations.
This has been evidenced by coloration measurement in slightly doped oxide cristal




<u>The doping vision (in cristal)</u>:

By changing the $V_O^{2+}$ distribution, two doping region can be formed, n and p respectively. For highly doped TMO, the n-type can become highly conductive




Slightly Fe doped STO

Red: $Fe^{4+}$, p-type region
White: $Fe^{<4+}$, n-type region (Vo rich)

# Valence Change Memory (redox-based)

In the case of thin films, the TMO are most of the time amorphous. But still, the $V_O^{2+}$ are expected to be the mobile species (no direct evidence of $V_O^{2+}$ migration in amorphous TMO)

<u>The stochiometry vision</u> :

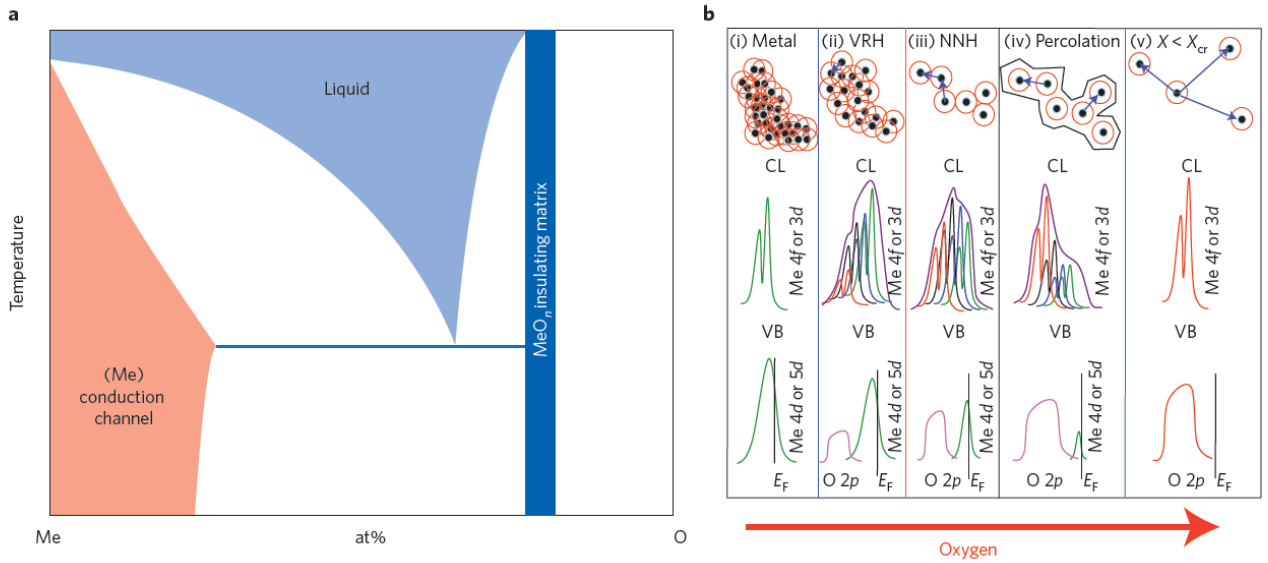
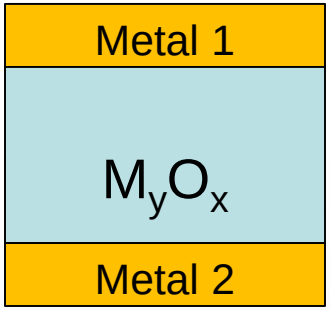



**Figure 2 | Material selection criteria for high endurance and repeatability. a**, Simplified schematic phase diagram of a metal–oxygen (Me–O) system with only two solid-state phases at low temperature. The $MeO_n$ phase is an insulating stoichiometric phase, serving as the matrix material in the switching device illustrated schematically in Fig. 1. The (Me) phase is a metal–oxygen solid solution, serving as the conduction channel. These two phases are thermodynamically stable with each other and do not mix by reaction to form an intermediate phase even at high temperature, for example, locally induced by Joule heating. The metal (Me) has a large solubility of oxygen, readily accommodating mobile oxygen anions or vacancies during switching. **b**, With increasing oxygen content in the channel region, the electron transport mechanism changes, producing corresponding resistance changes. The schematic depicts a sequence of evolving conduction centre density and conduction mechanisms (top), and corresponding photoemission core-level (CL, middle) and valence-band (VB, bottom) measurements, from a disordered transition metal oxide in the course of oxidation. The red circles are the localization radii. Unoxidized metallic state (i), weakly localized variable range hopping (VRH) regime (ii), more strongly localized nearest-neighbour hopping (NNH, iii), strong localization regime on the verge of percolation breakdown (iv), and final highly insulating sub-percolation insulating state (v). $X$ is the fraction of conduction centre sites and $X_{cr}$ is the critical fraction at the percolation threshold. $E_F$, Fermi energy. Panel **b** reproduced with permission from ref. 73, © 2012 Springer.

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| Insulators | Bottom Electrode | Top electrode | Switching mode | reference |
|---|---|---|---|---|
| MgO | Pt | Pt | Unipolar | 1 |
| TiOx | Ru, Pt | Al, Pt | Non/Uni/Bipolar | 2, 3 |
| $ZrO_x$ | $P^+$-Si , $n^+$-Si | Pt, Cr | Uni/Bipolar | 4-6 |
| $HfO_x$ | TiN | TiN | Bipolar | 7 |
| $VO_x$ | N/A | N/A | Threshold | 8, 9 |
| $NbO_x$ | $P^+$-Si | Pt | Unipolar | 10 |
| $TaO_x$ | Pt, Ta | Pt, Ta | Bipolar | 11, 12 |
| $CrO_x$ | TiN | Pt | Bipolar | 13 |
| $MoO_x$ | Pt | Pt-Ir | Uni/Bipolar | 14 |
| $WO_x$ | W, FTO | TiN, Au | Bipolar | 15, 16 |
| $MnO_x$ | Pt | Al, TiN | Bipolar | 17, 18 |
| $FeO_x$ | Pt | Pt | Non/Bipolar | 19, 20 |
| $CoO_x$ | Pt | Pt | Nonpolar | 21 |
| $NiO_x$ | Pt | Pt | Nonpolar/Threshold | 22, 23 |
| $CuO_x$ | TiN, TaN, SRO, Pt | Pt | Bipolar | 24 |
| $ZnO_x$ | Pt, Au | TiN, Ag | Bipolar | 25-27 |
| $AlO_x$ | Ru, Pt | Pt, Ti | Unipolar/Bipolar | 28, 29 |
| $GaO_x$ | ITO | Pt, Ti | Bipolar | 30 |
| $SiO_x$ | Poly-Si, TiW | Poly-Si, TiW | Unipolar | 31 |
| $SiO_xN_y$ | W | Cu | Bipolar | 32 |
| $GeO_x$ | ITO, TaN | Pt, Ni | Bipolar | 33, 34 |
| $SnO_2$ | Pt | Pt | Unipolar | 35 |
| $BiO_x$ | Bi | W, Re, Ag, Cu | Bipolar | 36 |
| $SbO_x$ | Pt | Sb | Unipolar/Bipolar | 37 |
| $SmO_x$ | TiN | Pt | Bipolar | 38 |
| $GdO_x$ | Pt | Pt | Unipolar | 39 |
| $YO_x$ | Al | Al | Unipolar | 40 |
| $CeO_x$ | Pt | Al | Bipolar | 41 |
| $EuO_x$ | TaN | Ru | Uni/Bipolar | 42, 43 |
| $PrO_x$ | TaN | Ru | Bipolar | 42, 43 |
| $ErO_x$ | TaN | Ru | Unipolar | 42, 43 |
| $DyO_x$ | TaN | Ru | Unipolar | 42, 43 |
| $NdO_x$ | TaN | Ru | Unipolar | 42, 43 |
| $Ba_{0.7}Sr_{0.3}TiO_3$ | $SrRuO_3$ | Pt, W | Bipolar | 44 |
| $SrTiO_3$ | $SrRuO_3$, Au, Pt | Au, Pt | Bipolar | 45 |
| $SrZrO_3$ | $SrRuO_3$ | Au | Bipolar | 46 |
| $BiFeO_3$ | $LaNiO_3$ | Pt | Bipolar | 47 |
| $Pr_{0.7}Ca_{0.3}MnO_3$ | YBCO, Pt, $LaAlO_3$ | Ag | Bipolar | 48 |
| $La_{0.33}Sr_{0.67}FeO_3$ | Au | Al | Bipolar | 49 |
| $Pr_yLa_{0.625-y}Ca_{0.375}MnO_3$ | Ag | Ag | Bipolar | 50 |
| Nitrides (AlN) | Al, TiN, Pt | Al, TiN, Pt | Bipolar | 51 |
| Telluride (ZnTe) | Si | Au | Bipolar | 52 |
| selenide (ZnSe) | $P^+$-Ge | In, In-Zn | Bipolar | 53 |
| Polymers | Al, ITO, Cu | Al, ITO, Cu | Bipolar | 54, 55 |

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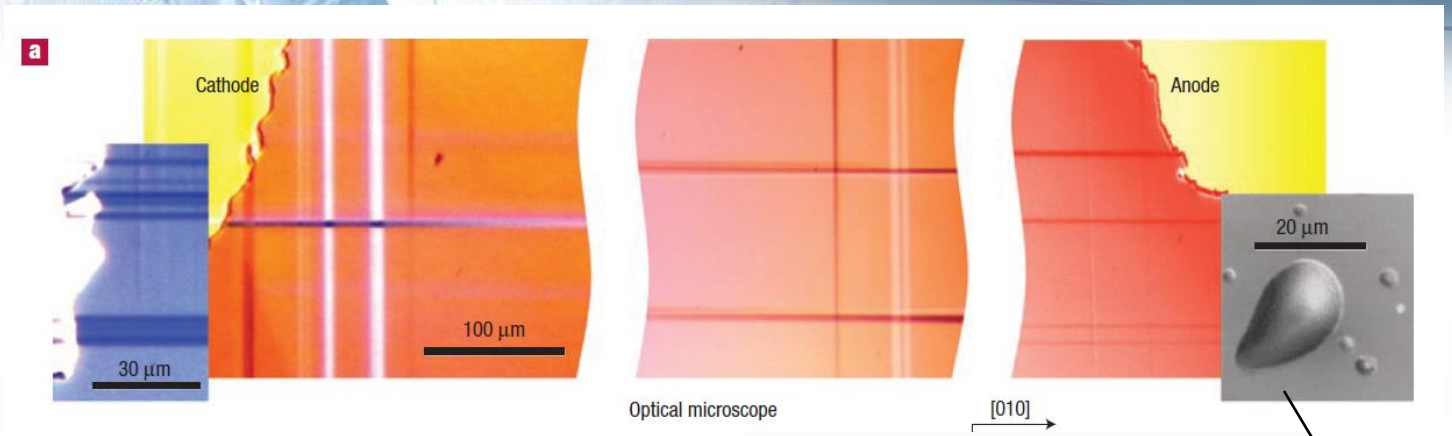
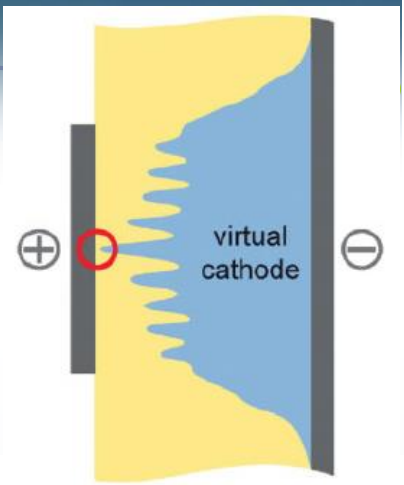
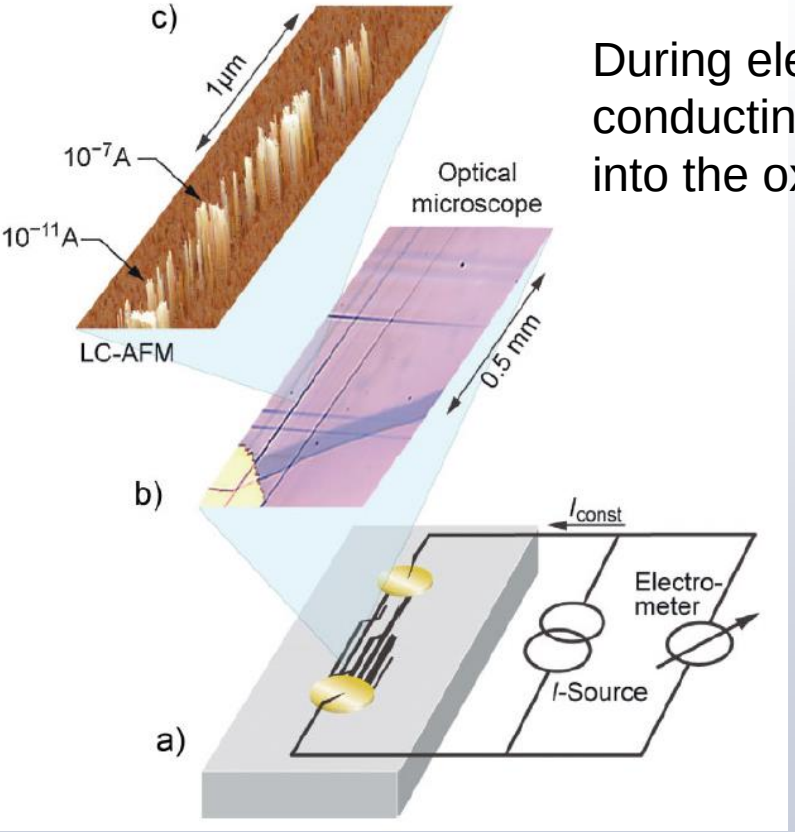
# Electroforming (cristal)

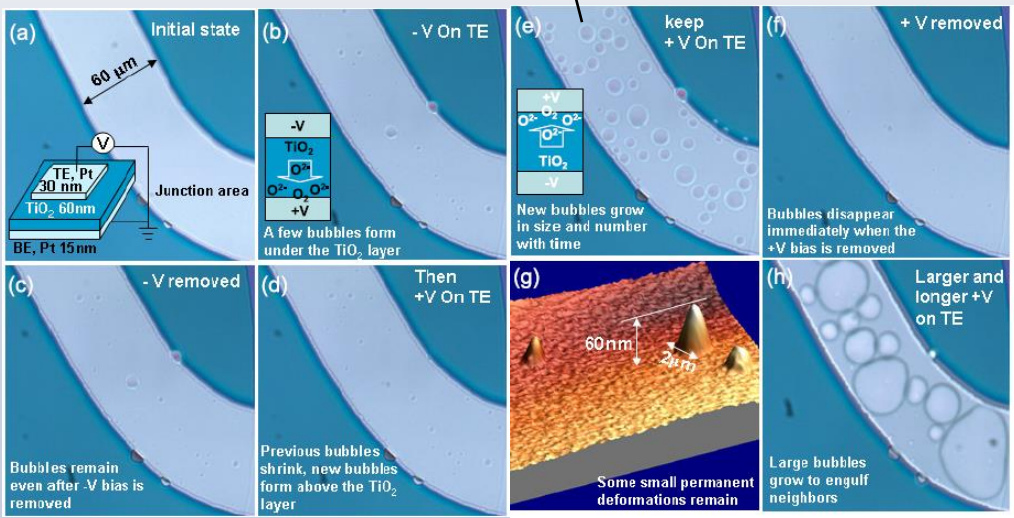



During electroforming, conducting filament are created into the oxide.

$$O_O \rightleftharpoons \frac{1}{2}O_2(g) + V_O^{\bullet\bullet} + 2e'$$

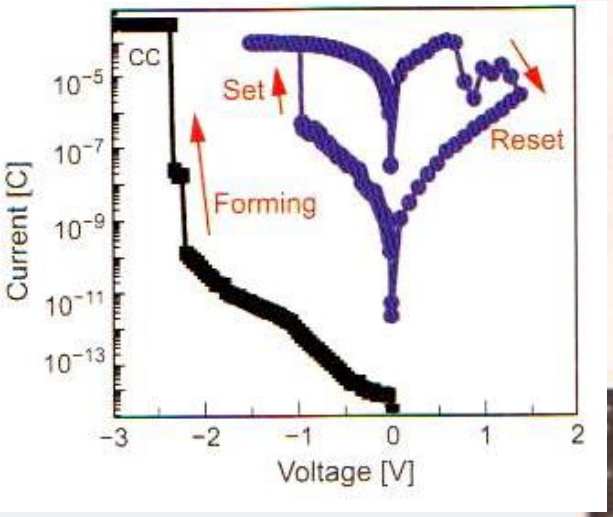


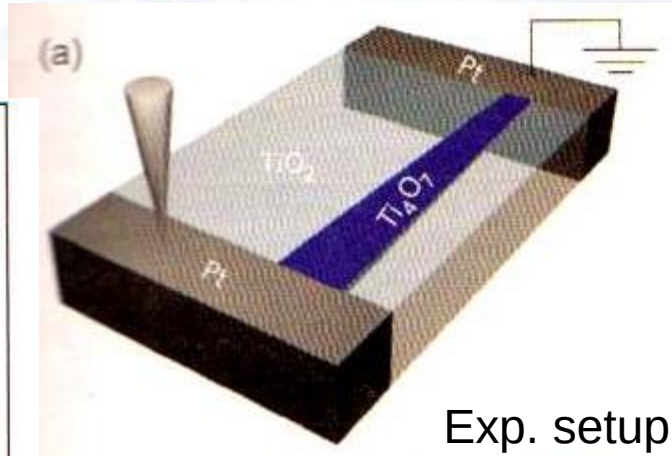



# Electroforming (thin film)

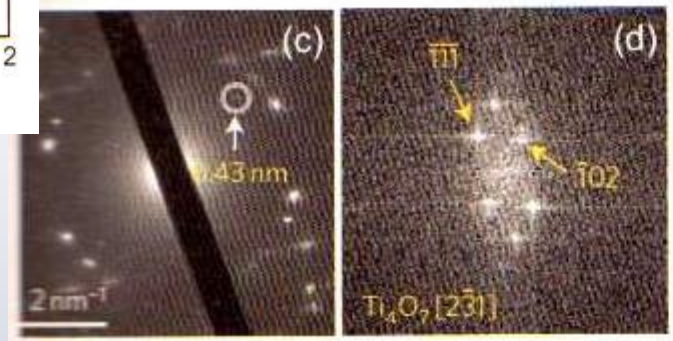
## Observation of Magneli phases in TiO2

Example of forming

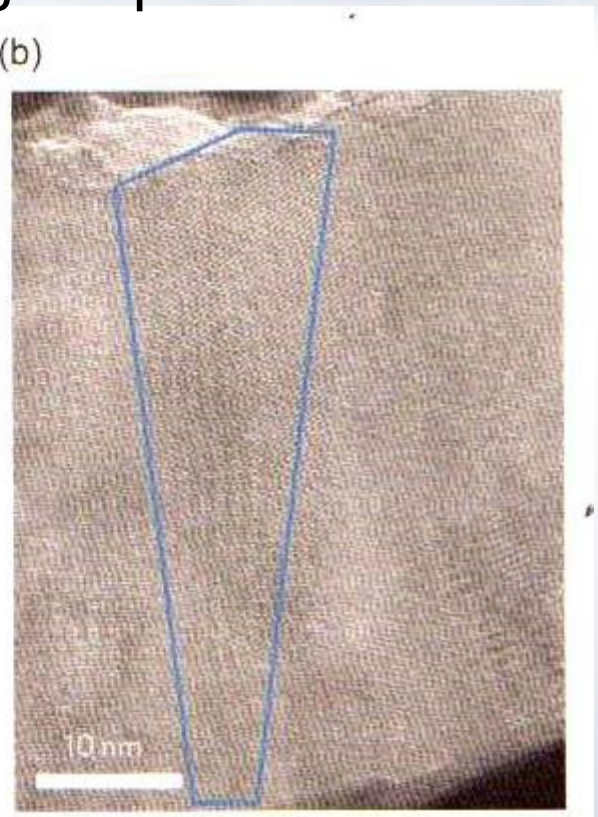



Exp. setup



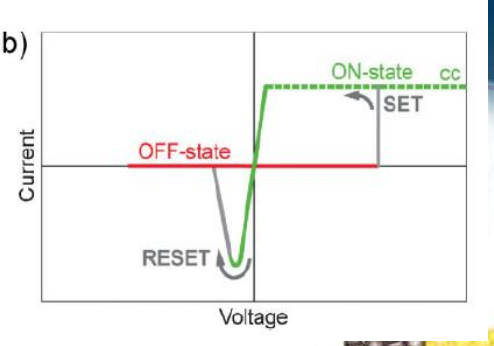

X ray-diffraction




TEM image

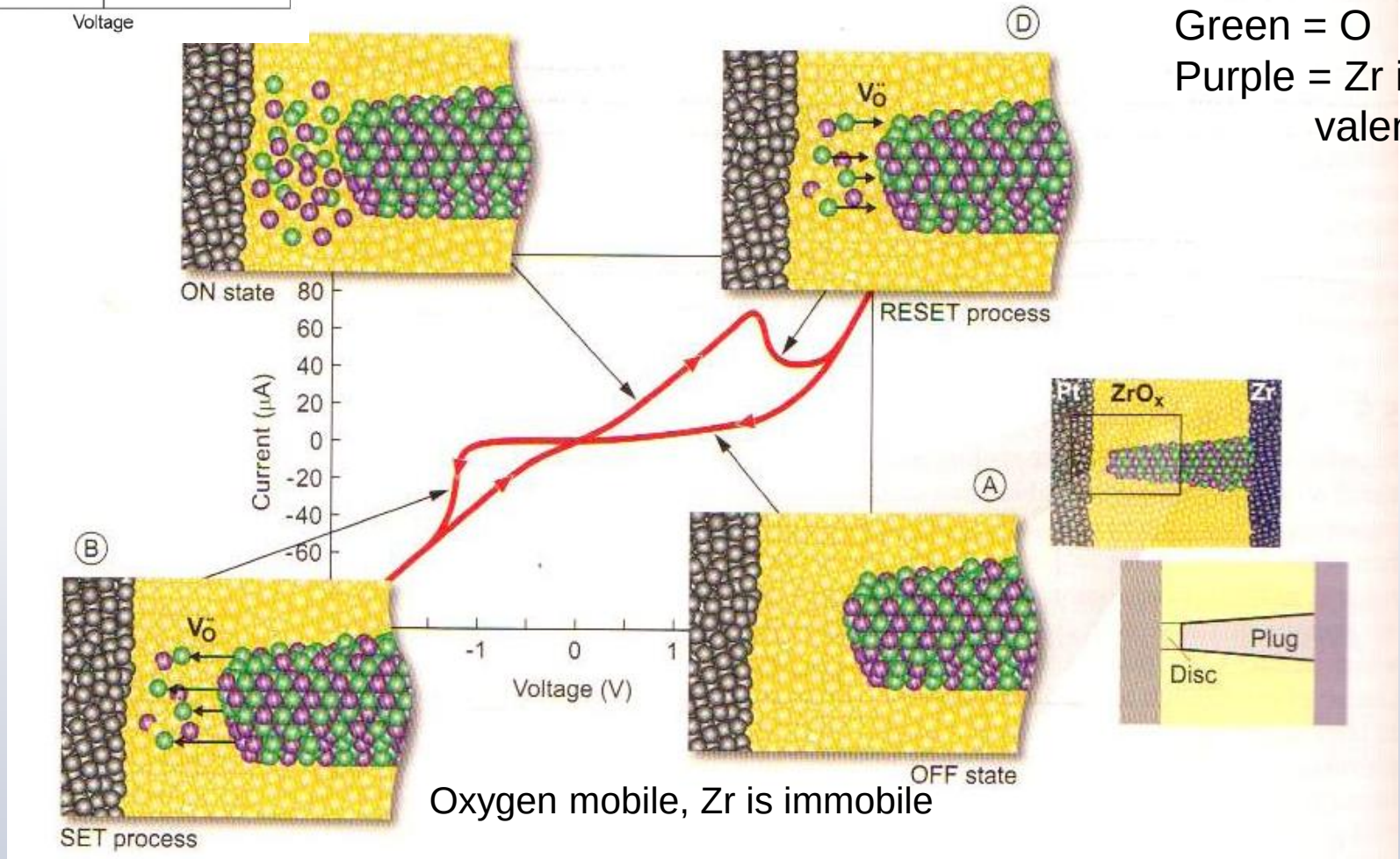
- Forming is thermally assisted and two step process (reduction and migration)

# Bipolar switching



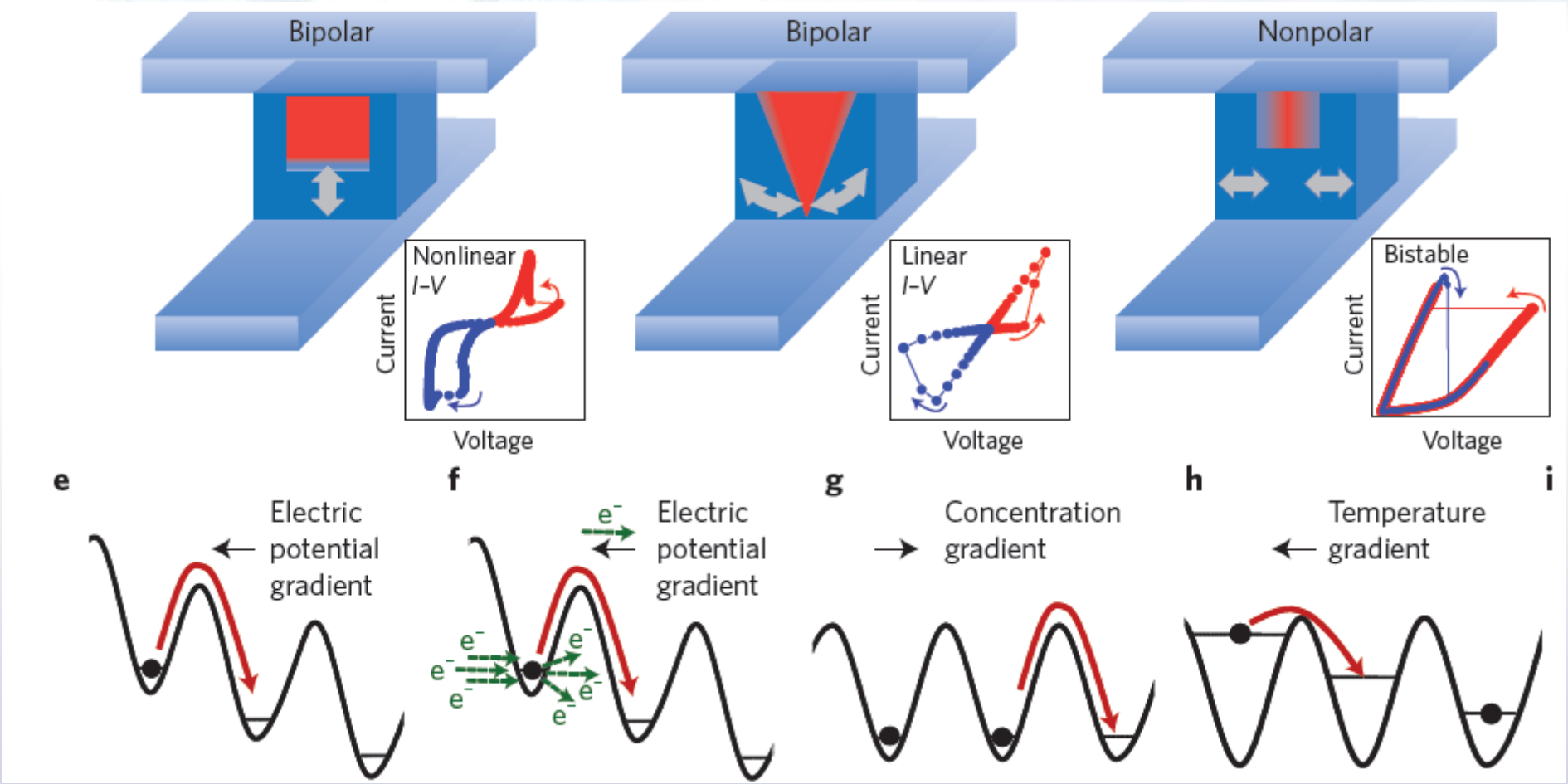

## $Pt/ZrO_x/Zr$

Green = O
Purple = Zr in lower valence state




Oxygen mobile, Zr is immobile

# Mechanism for switching




Practically, even if one mechanism is more important, switching results from a combination

# Non linearity

$$\mu_{Vo} = \frac{z_{Vo} e_0}{kT} D_0 \exp(-W_D/kT)$$

Vacancies mobility increase exponentially with temperature

Other factor:

- Maybe the stability of the two phases (i.e. stochiometric vs high $V_O^{2+}$ concentration)

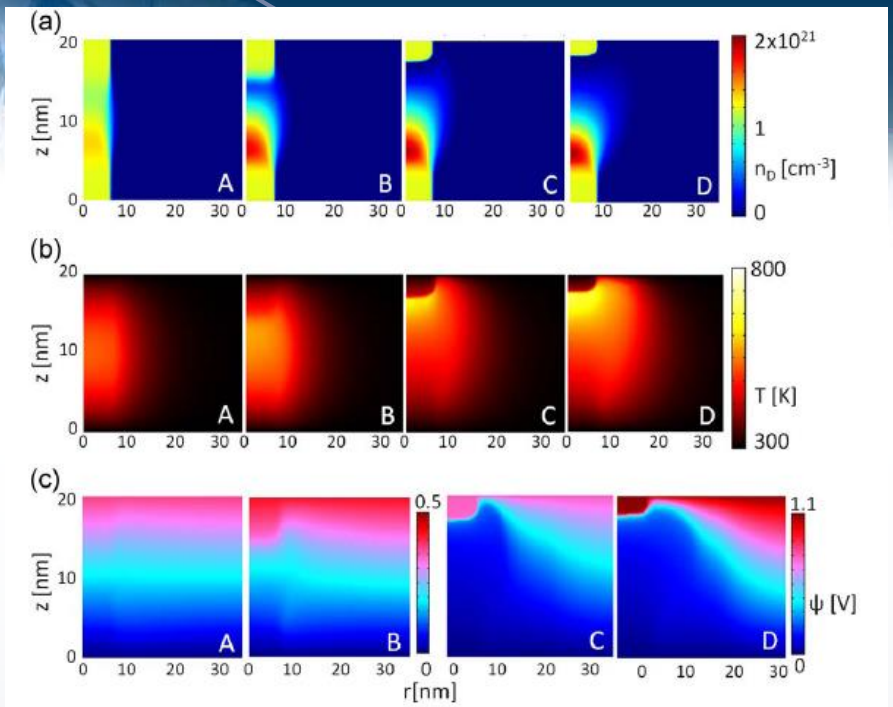
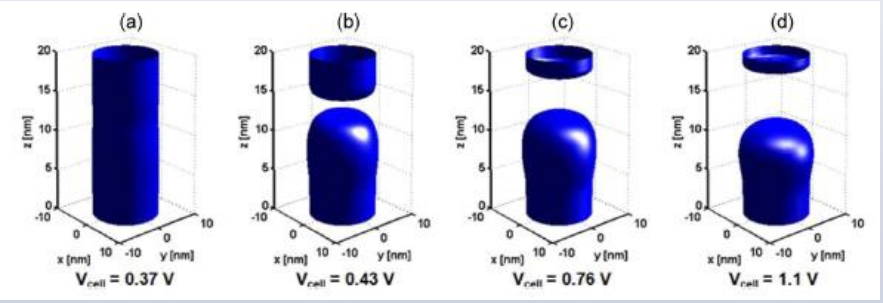
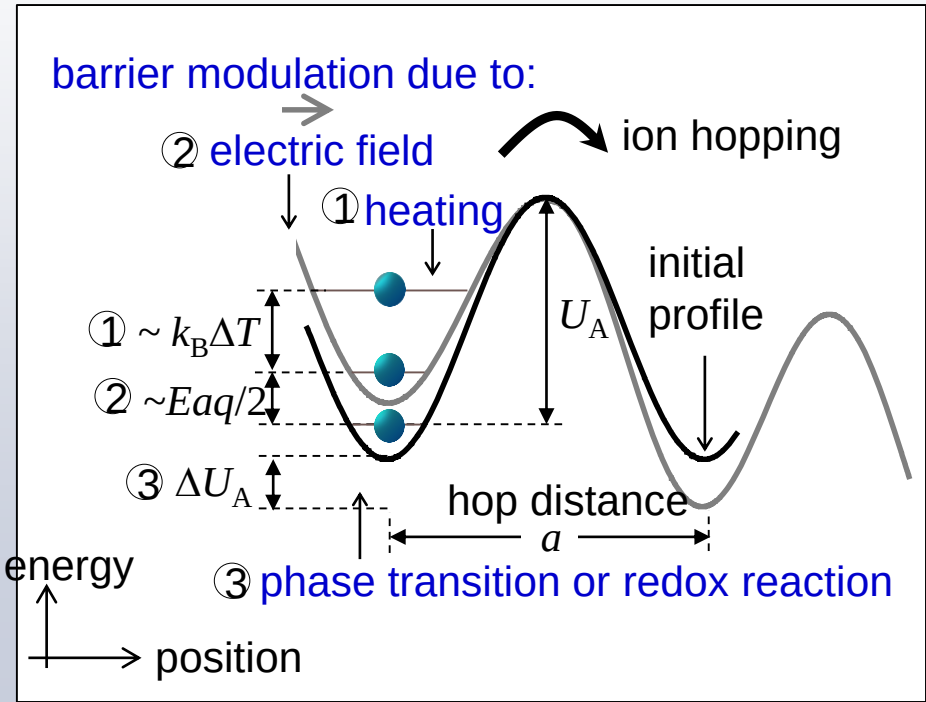



Fig. 5. Calculated map of (a) dopant density $n_D$, (b) $T$, and (c) potential $\psi$ for bias points A, B, C, and D along the reset sweep in Fig. 4(a). Calculations are shown as a function of radial coordinate $r$ and vertical coordinate $z$ according to Fig. 1.

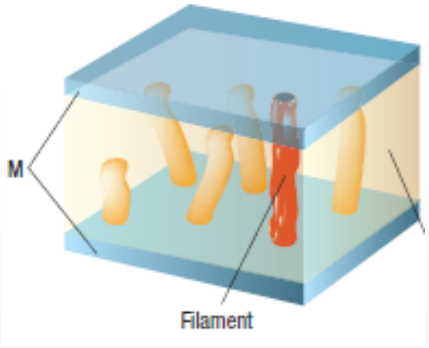


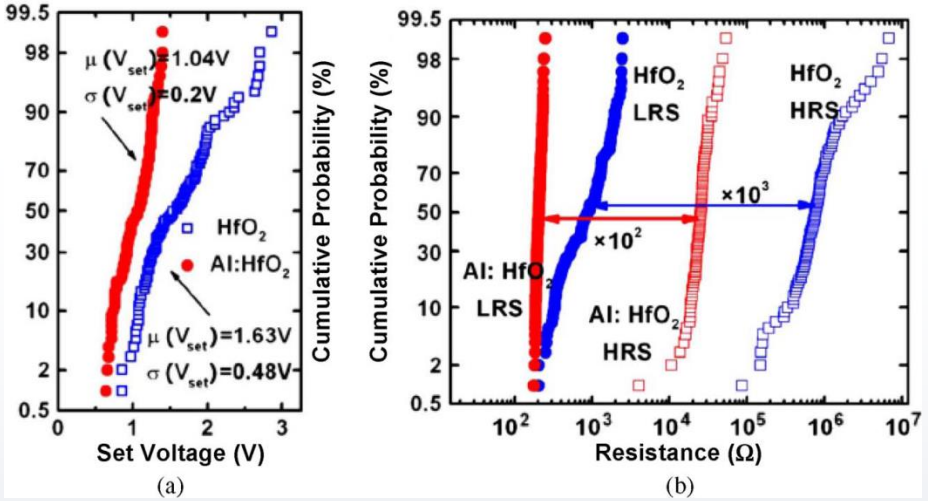



# RRAM Challenges

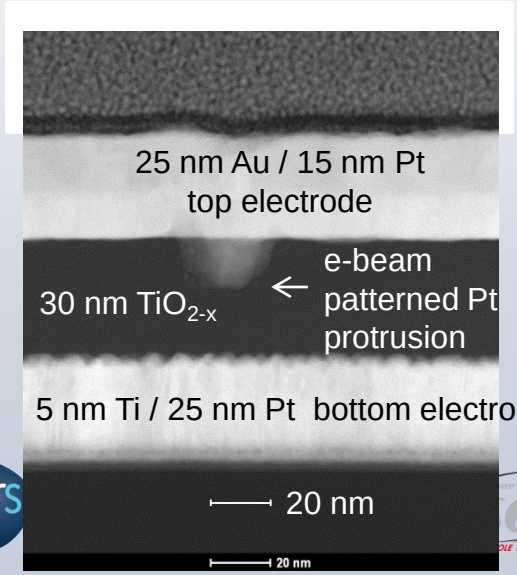
Main challenge: deal with dispersion

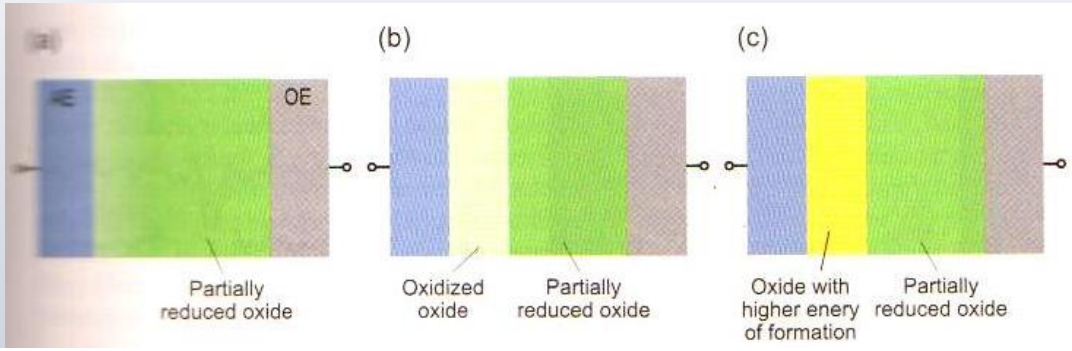
Because forming is stochastic, dispersion in switching properties are huge




Solution: towards forming free devices




AE = active electrode (low oxygen affinity, high work function, e.g Pt, Ir, TiN)
OE = Ohmic electrode (opposite, e.g Ti, Ta)

(a) Homogeneous monolayer, e.g. TiO2-x – forming is crucial
(b) Homogeneous bi-layer, e.g. TiO2/TiO2-x or Ta2O5/TaOx
(c) Hetergeneous bi-layer, e.g. Al2O3/TiO2-x or HfO2/TiO2-x

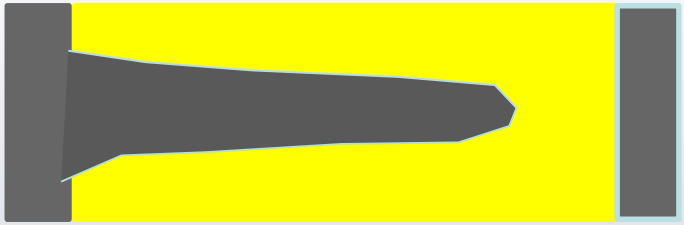
# RRAM Challenges

Main challenge: energy consumption

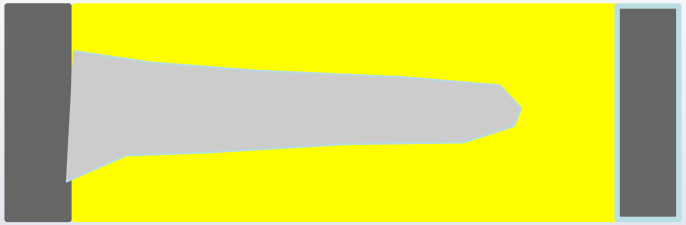
Lowest E/Bit reported is few pJ. Ideally, we want to go to the sub pJ regime

Solution: filament engineering
Trade off between filament resistance and ON/OFF ratio. (Need to increase the resistance of the filament)

High conductivity (metallic filament)



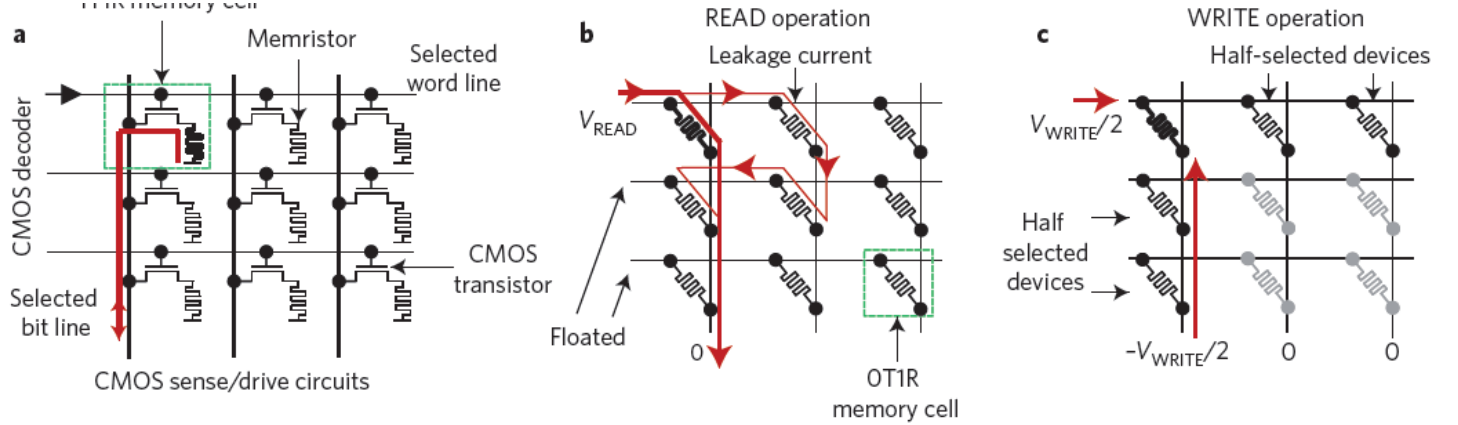
Moderate conductivity (Semi-metallic)



- Scaling of the filament
- Control of defects in the filament (i.e. control of conductivity)

# RRAM challenges

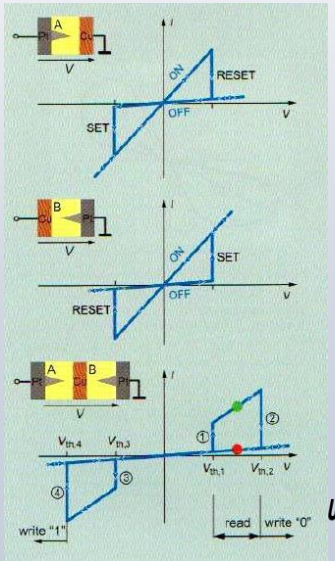
## Main challenge: high density crossbar implementation



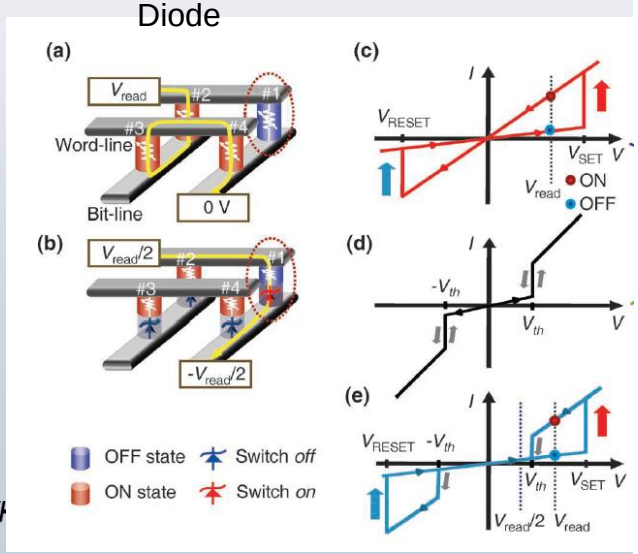

Additionnal challenges: Nanowire resistance contribution and high current effect on wire during operation

## Solutions:

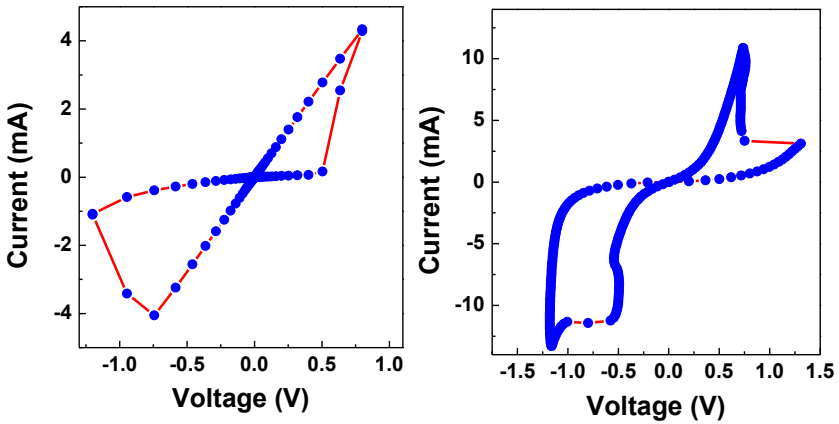
Complementary switching




Selector device:
Tunnel junction
S type
Diode




Intrinsic non-linear I-V



# Thanks for your attention