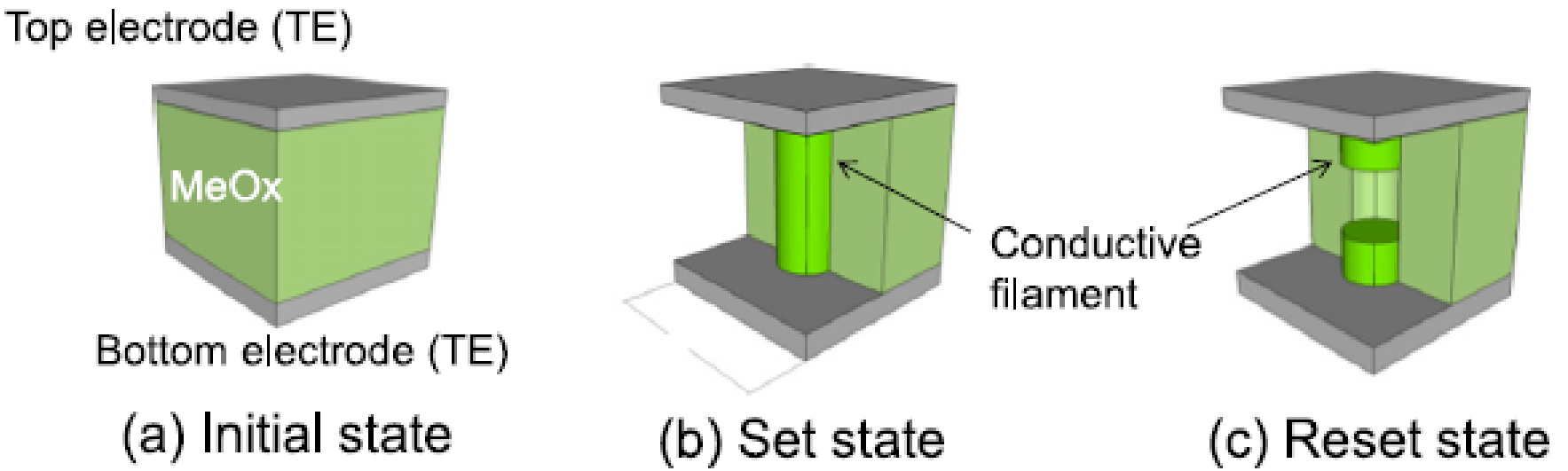
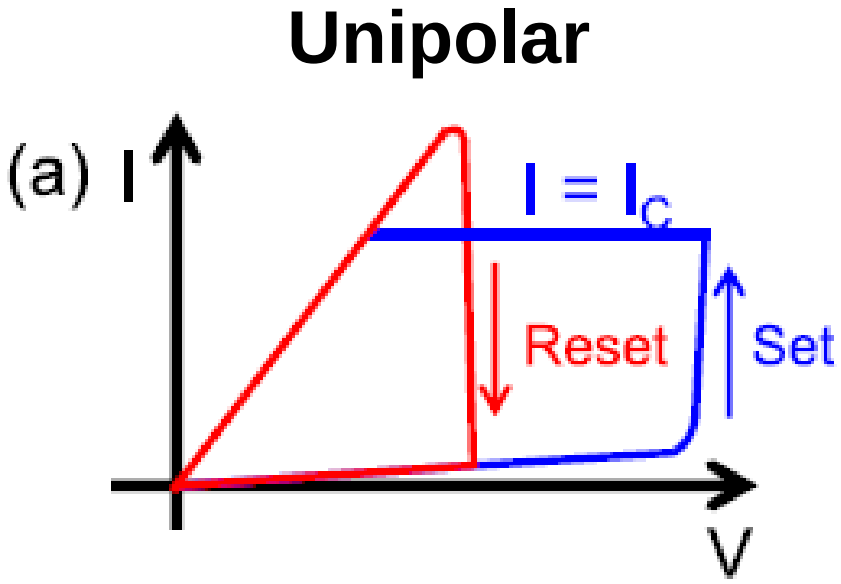
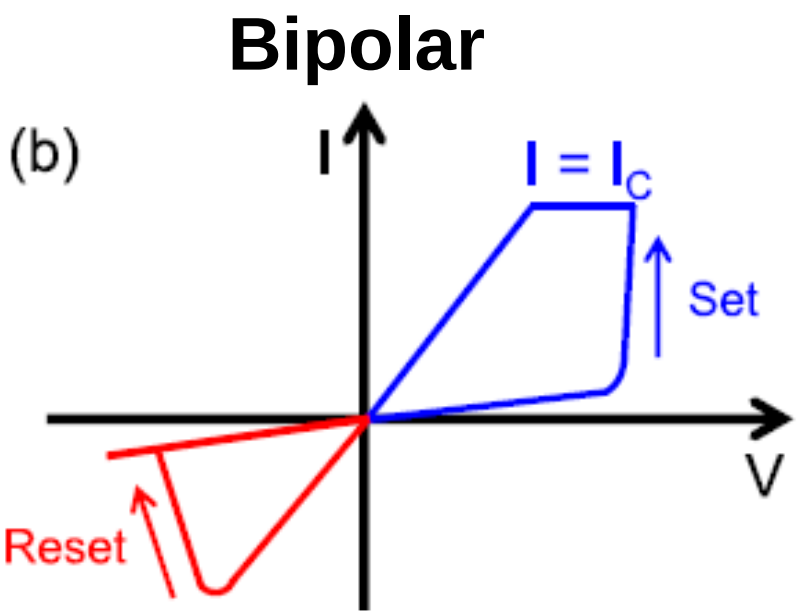
L6: Resistive RAM II

Recap

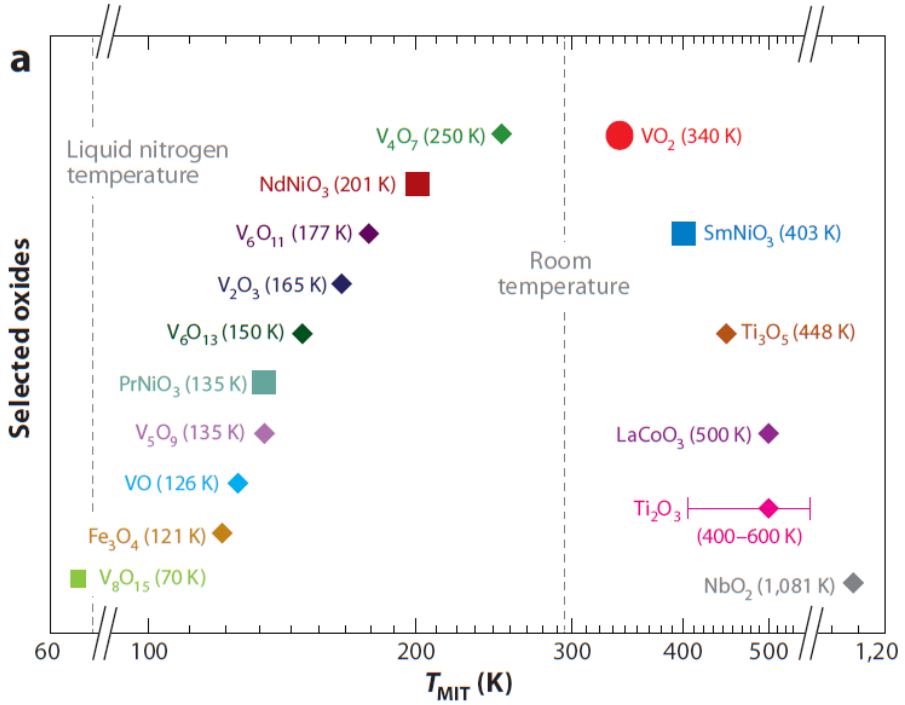

Top electrode (TE)
MeOx
Bottom electrode (TE)
(a) Initial state
Conductive filament
(b) Set state
(c) Reset state

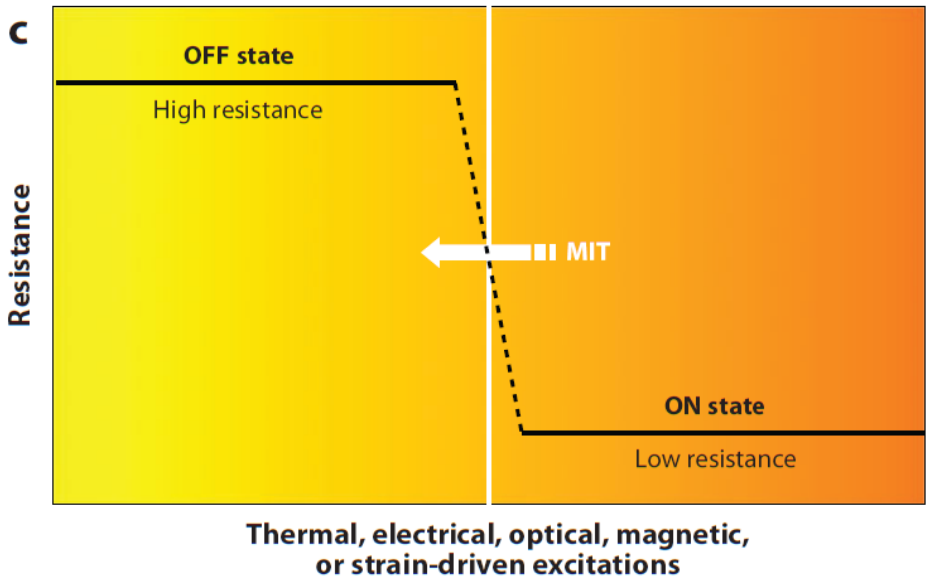

Unipolar
(a) I
I = I_C
Reset
Set
V


Bipolar
(b)
I
I = I_C
Set
V
Reset

Metal-Insulator Transition (MIT)

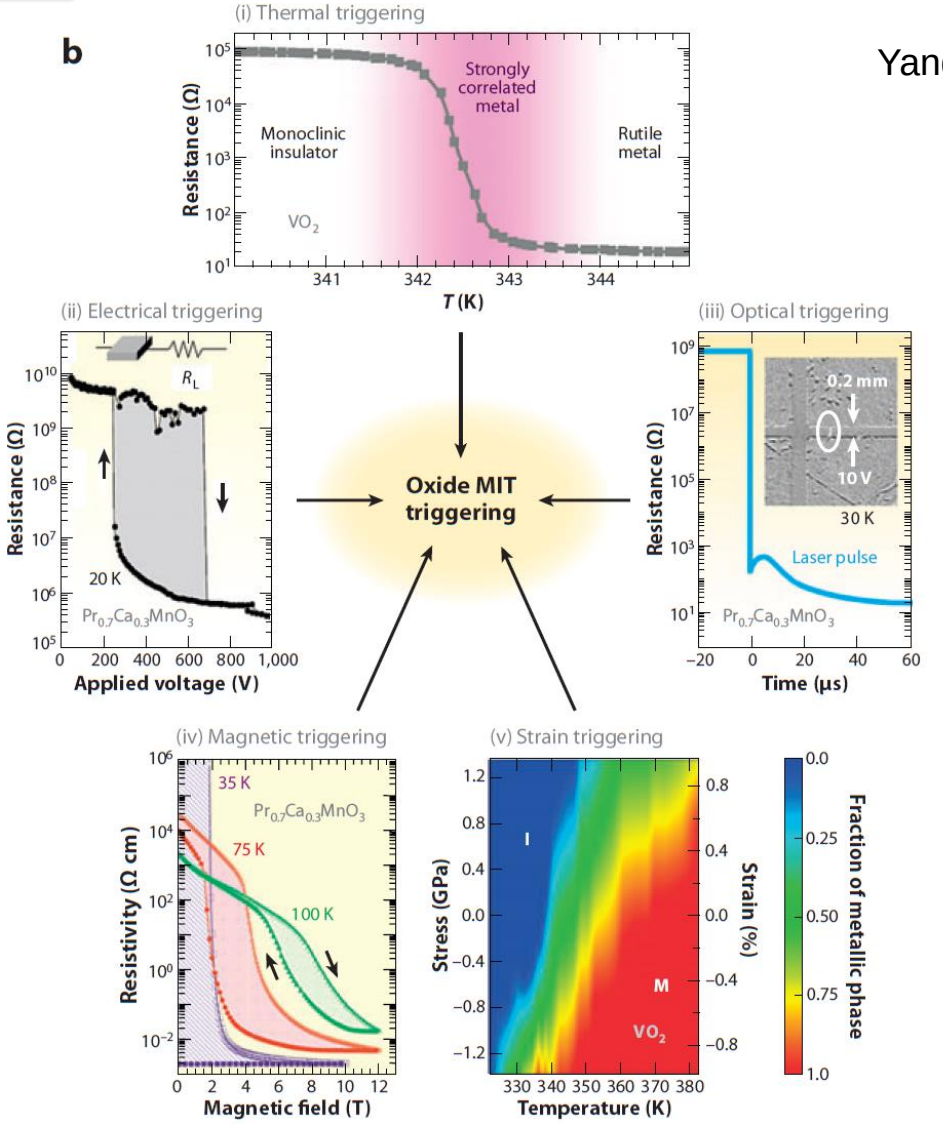
Yang et al., Annual Rev., 2011





- Metal-insulator transition
- Happens in metal oxides: VO_2, V_2O_3, VO and Ti_2O_3
- Transition temperature T_{MIT}

MIT Triggers



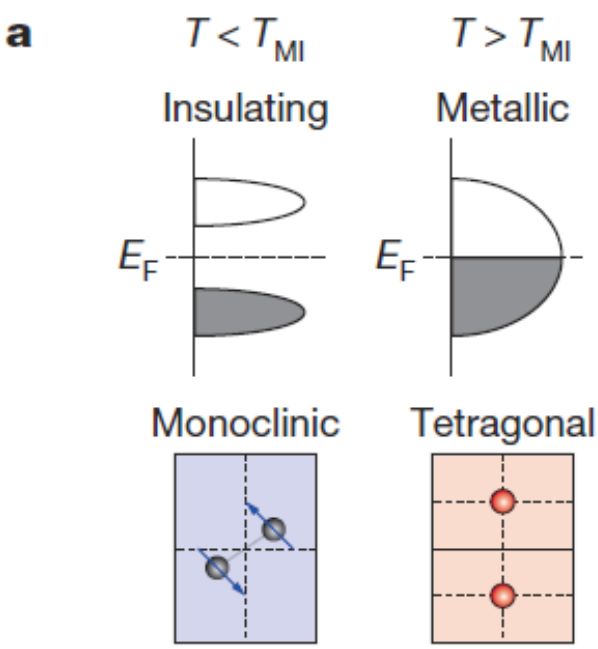
Yang et al., Annual Rev., 2011

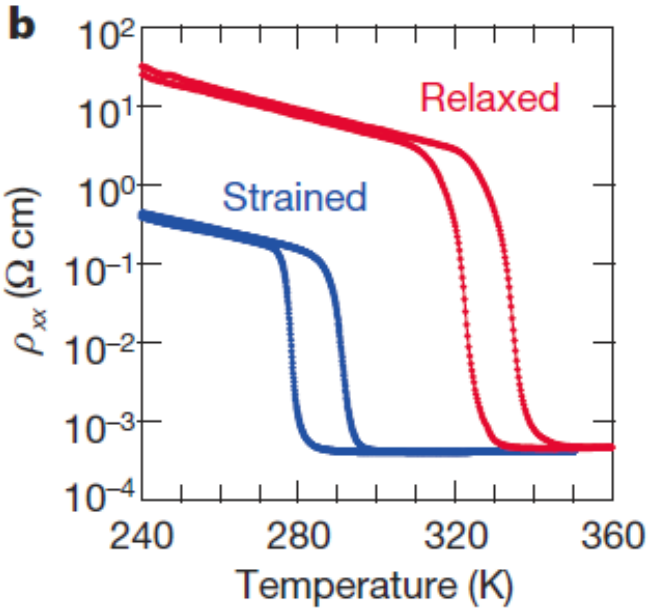
- Triggered thermally, electrically, optically and magnetically

MIT Induced by Temperature

- Vanadium dioxide VO_2
- Metal-Insulator transition T_{MIT} ~ 340 K or 67 C
- Tunable T_{MIT} via strain
- Low-Temp Monoclinic phase (3d electrons localized on V site)
- High-Temp tetragonal phase (mobile 3d electrons)

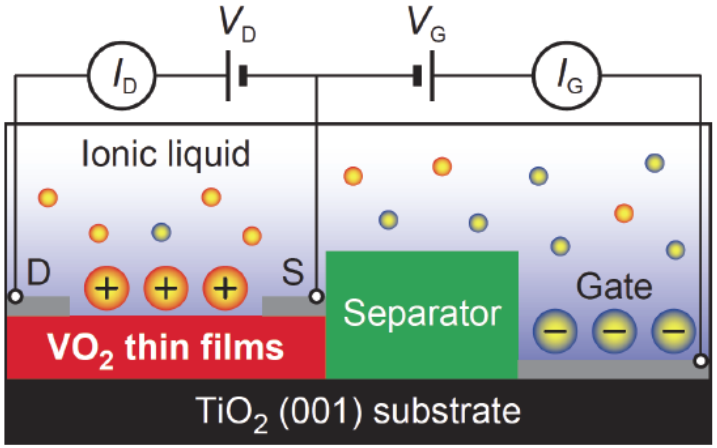
Nakano et al., Nature, 2012



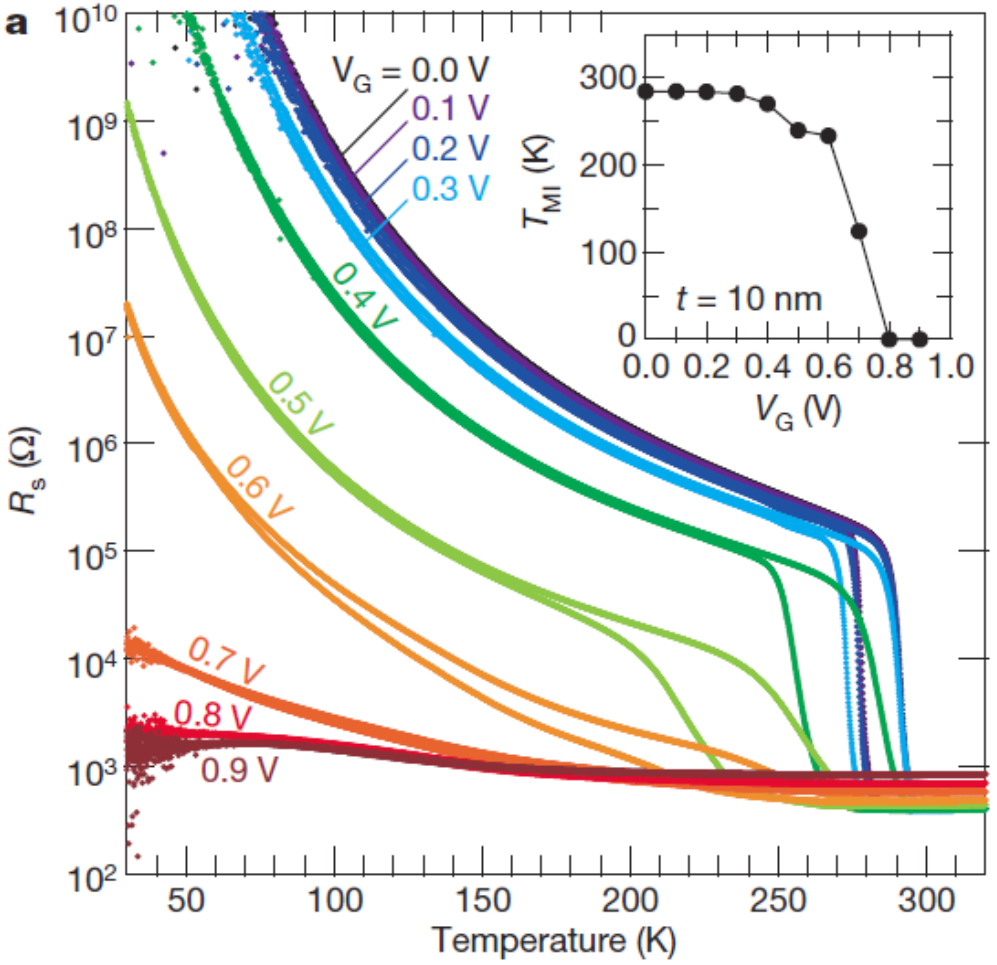


Inducing MIT with E-field

- No MIT has been achieved in VO_2 by pure electrostatic
  - requiring too high of an E-field
- T_{MIT} can be tuned by electron doping
  - ionic liquid gating → surface charge density 10^{15} cm^{-2}



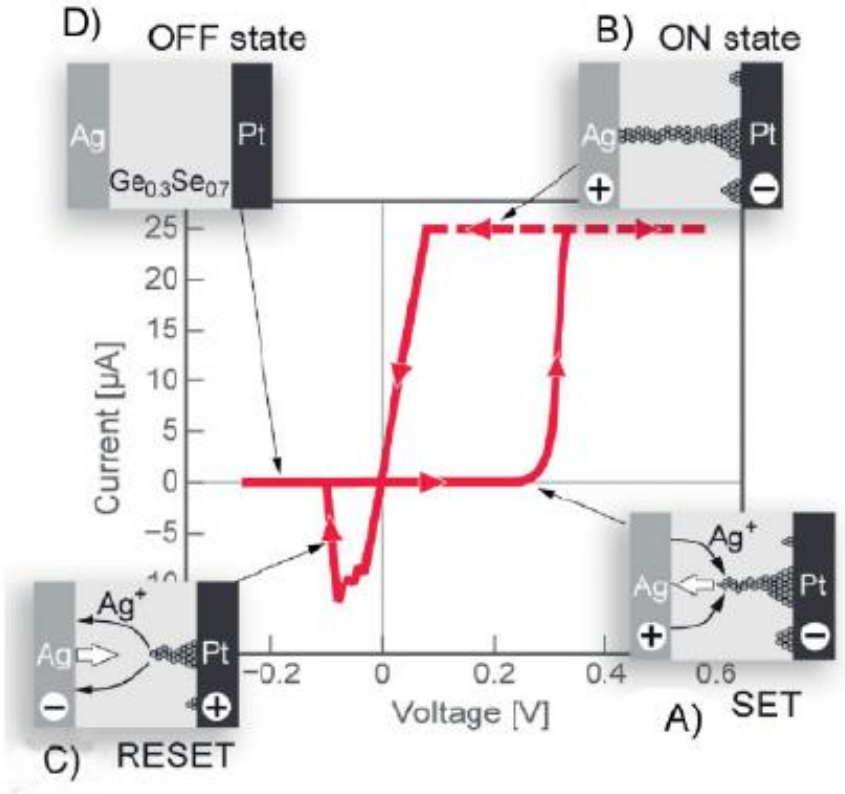
10 nm VO_2



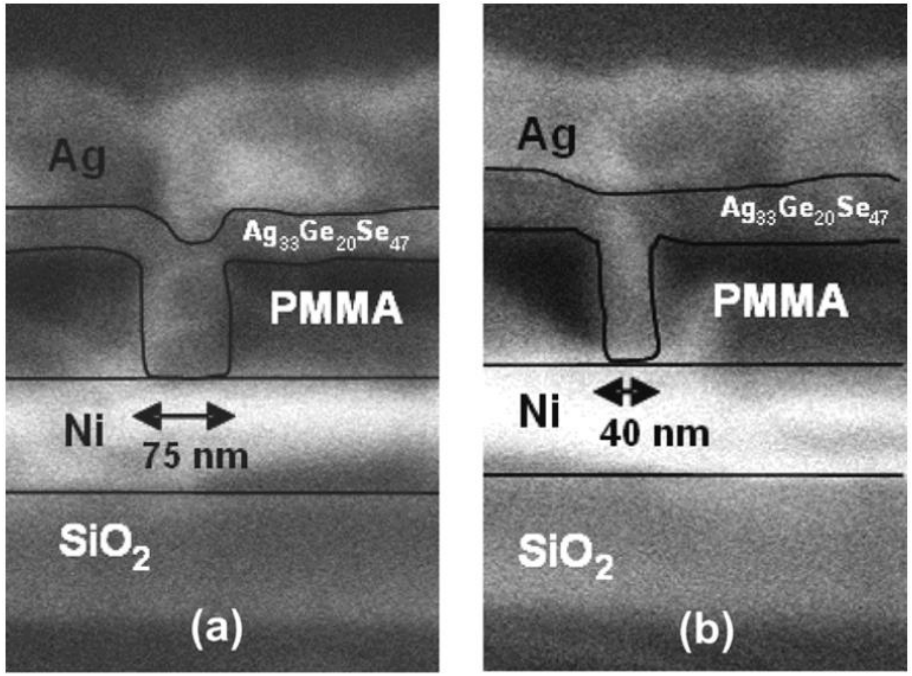
Nakano et al., Nature, 2012

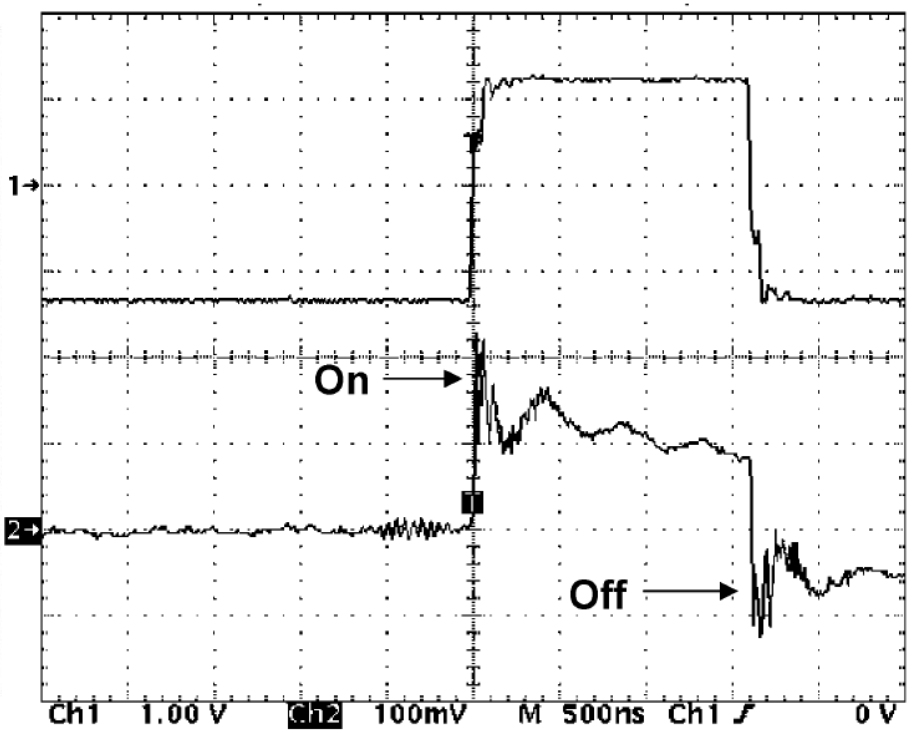
Electrochemical Metallization (ECM) Device

- Switching type: bipolar
- Switching material: chalcogenides (GeS, Ag_2S, etc), amorphous film (a-Si, a-C, etc)
- E-field driven redox reactions
- Metal filament formation
- Electrode plays an active role (e.g. Ag or Cu)



High Speed AgGeSe Device





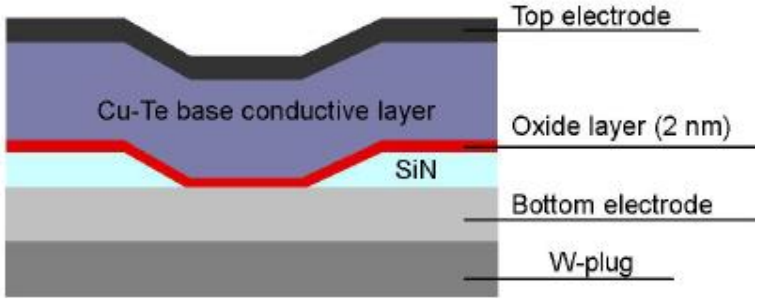
- AgGeSe compound with Ag electrode
- sub-70 ns switching speed

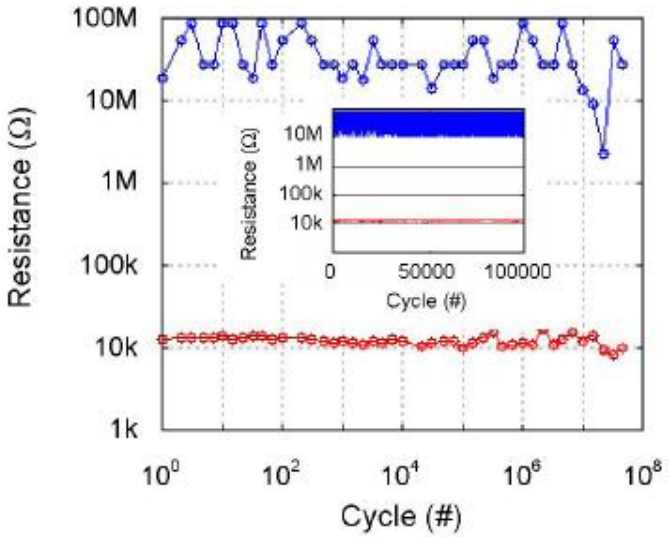
Kozicki et al., IEEE T-NANO, 2005

Cu-Te ECM Device

Table 1. Typical parameters and key features.

FEOL	180-nm CMOS
Active cell area	40 nmϕ
Set pulse width Set current Set voltage	5 ns 110 μA +3 V
Reset pulse width Reset current Reset voltage	1 ns 125 μA −1.7 V
Resistance read voltage	+0.1 V
Endurance	10^7 cycles



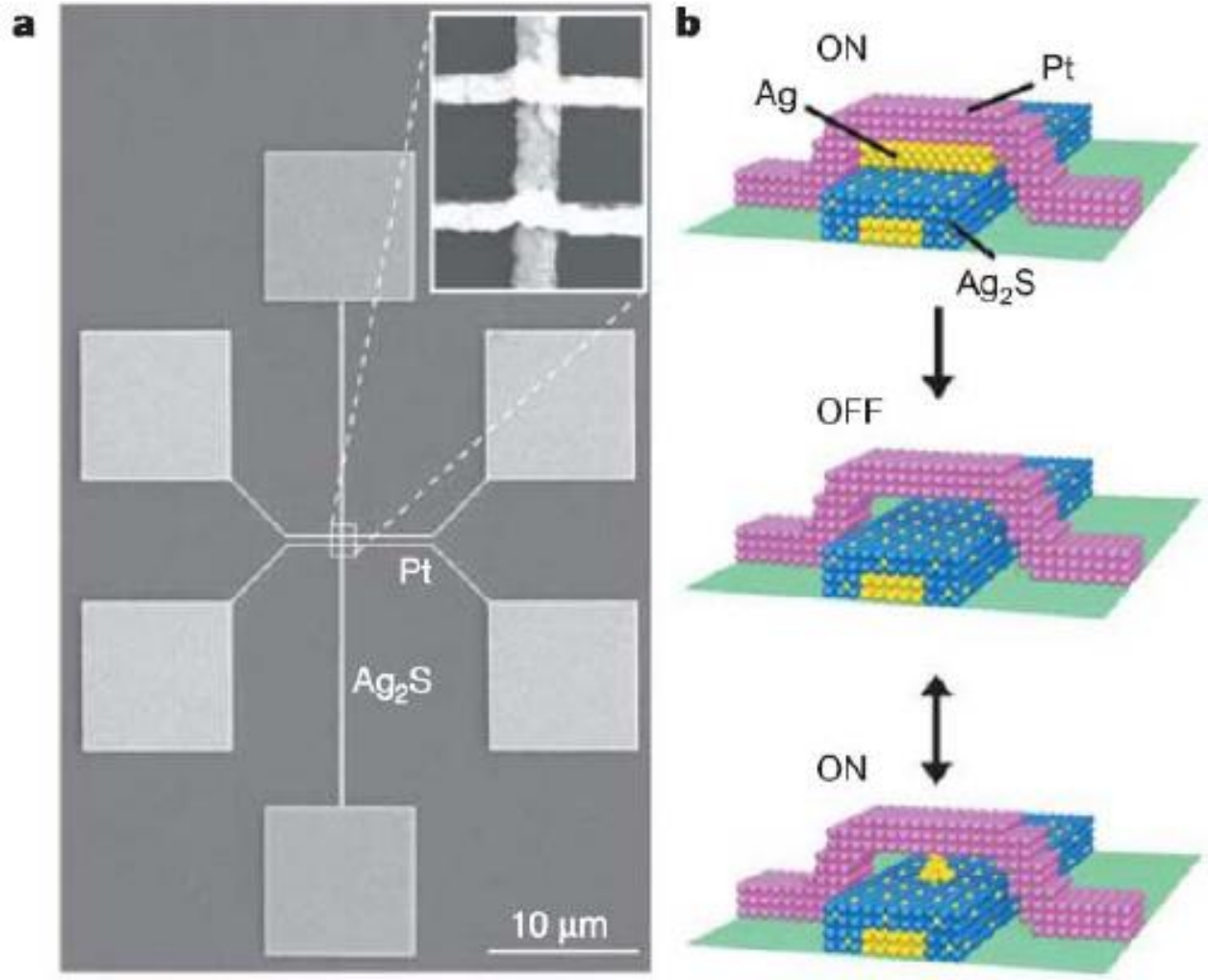


- High speed with good endurance

Aratani et al., IEDM, 2007

Au Atomic Switch

Terabe et al., Nature, 2005

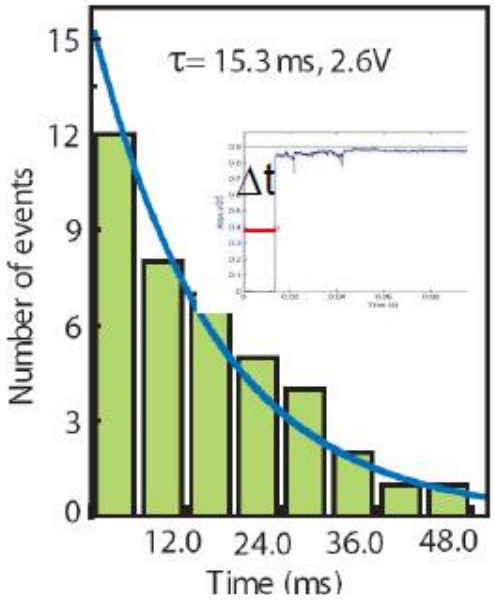


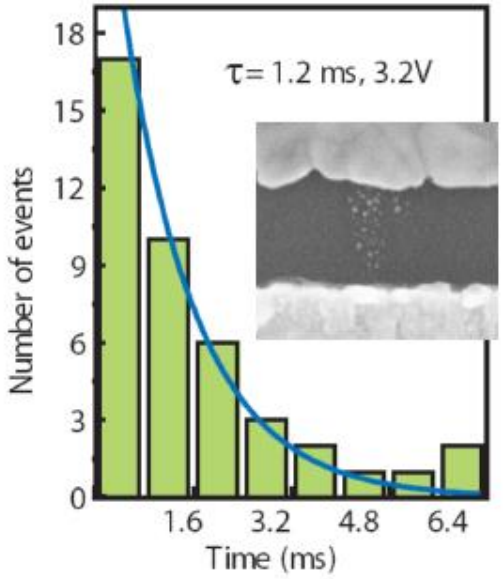
- Single Au atom bridge between TE and BE in Ag_2S

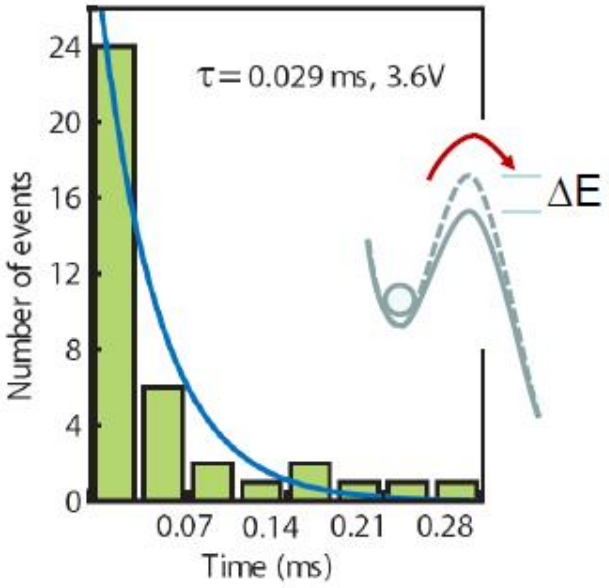
Stochastic Device

- Stochastic vs deterministic
- True random number generator
  - physical event: thermal noise, radioactive decay
  - too slow
- Filamentary formation is a stochastic process → following a Poisson distribution at a given condition

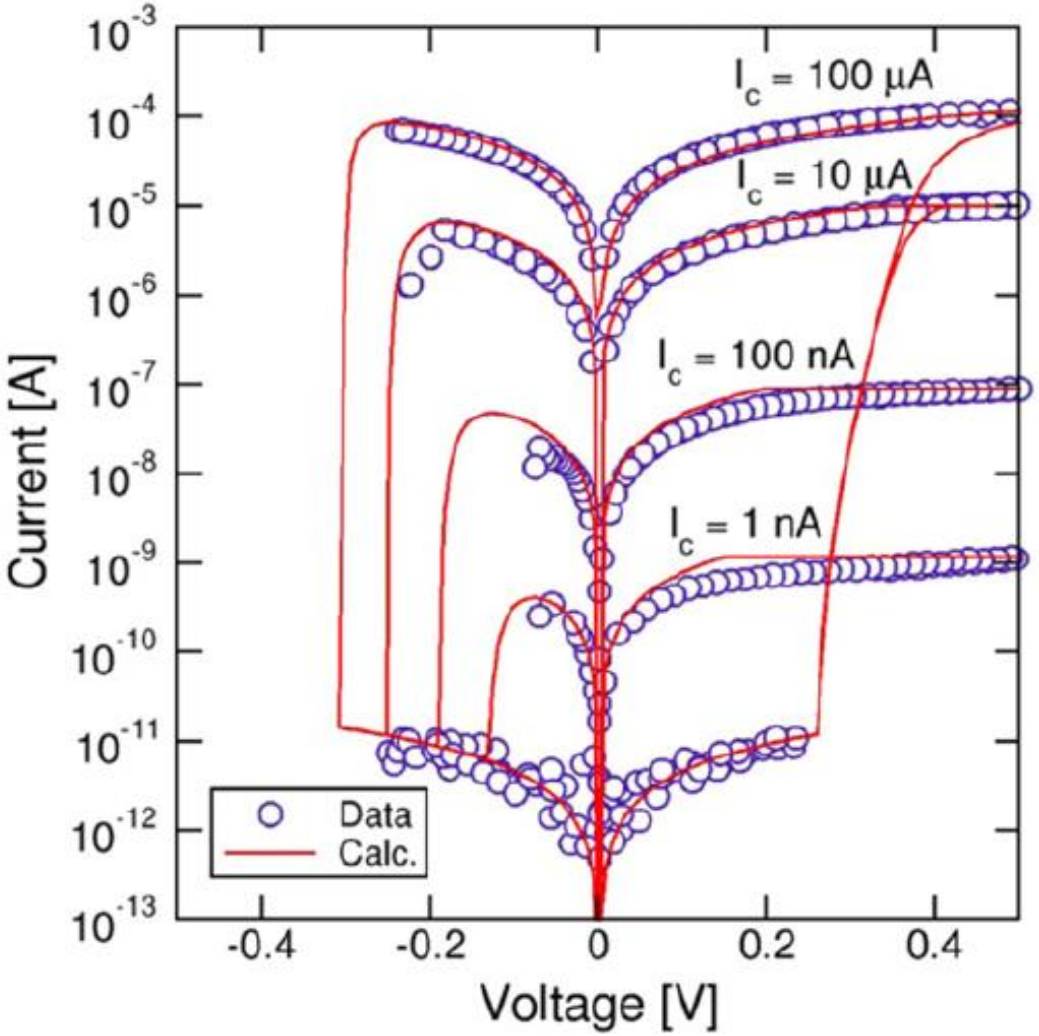
Gaba et al., Nanoscale, 2013







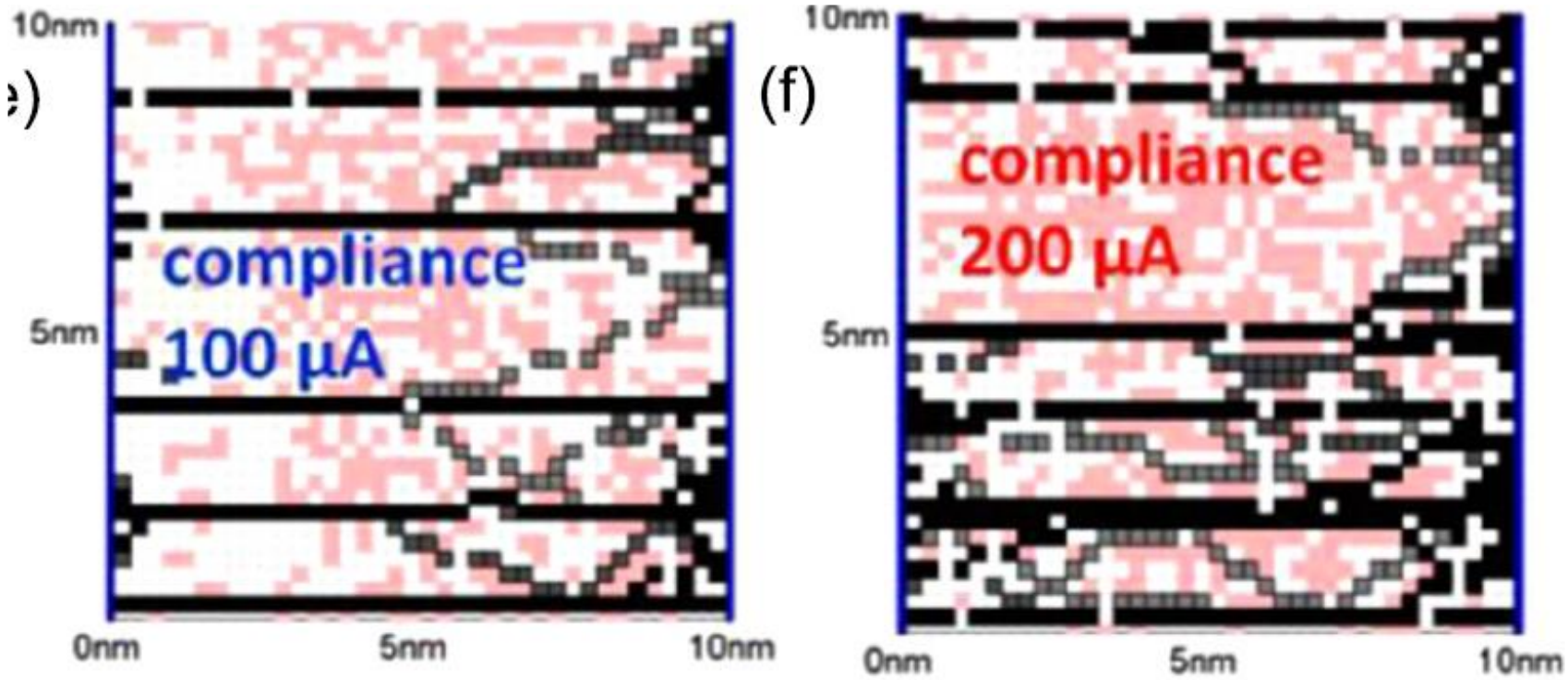
Effect of Compliance Current



Ielmini et al., SST., 2016

- Compliance determines filament size, thus on/off ratio and voltage

Modeling of Device

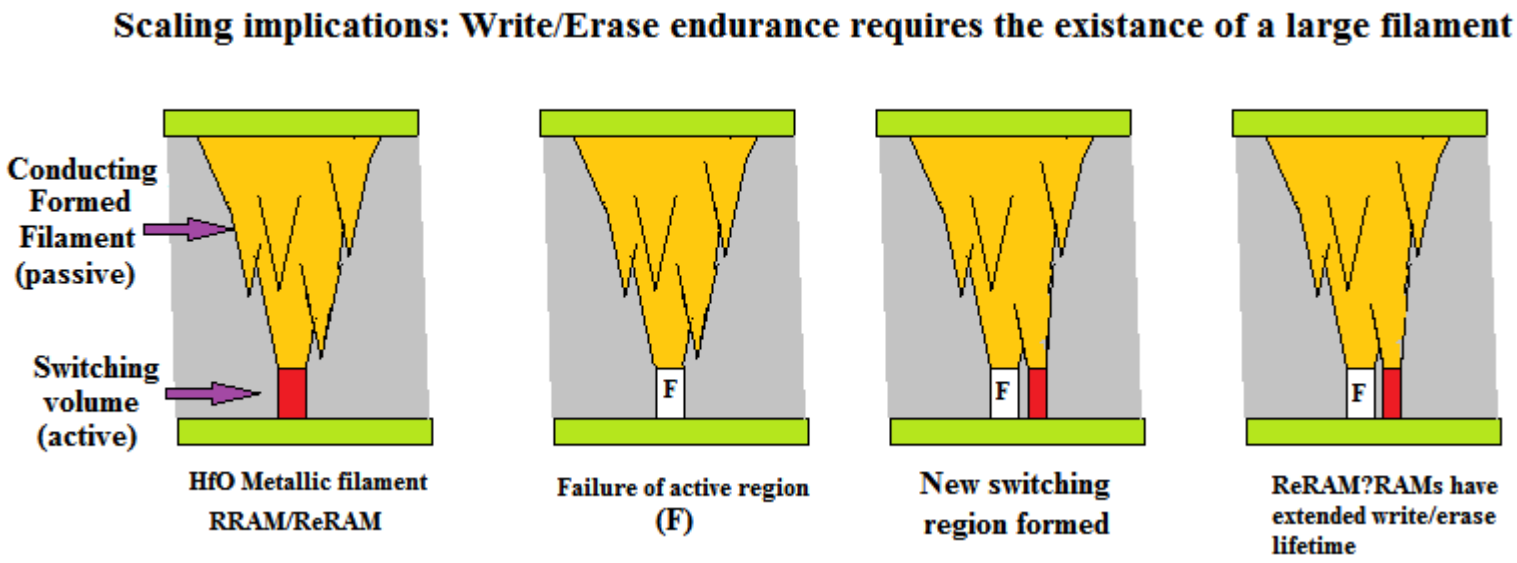


Ielmini et al., SST., 2016

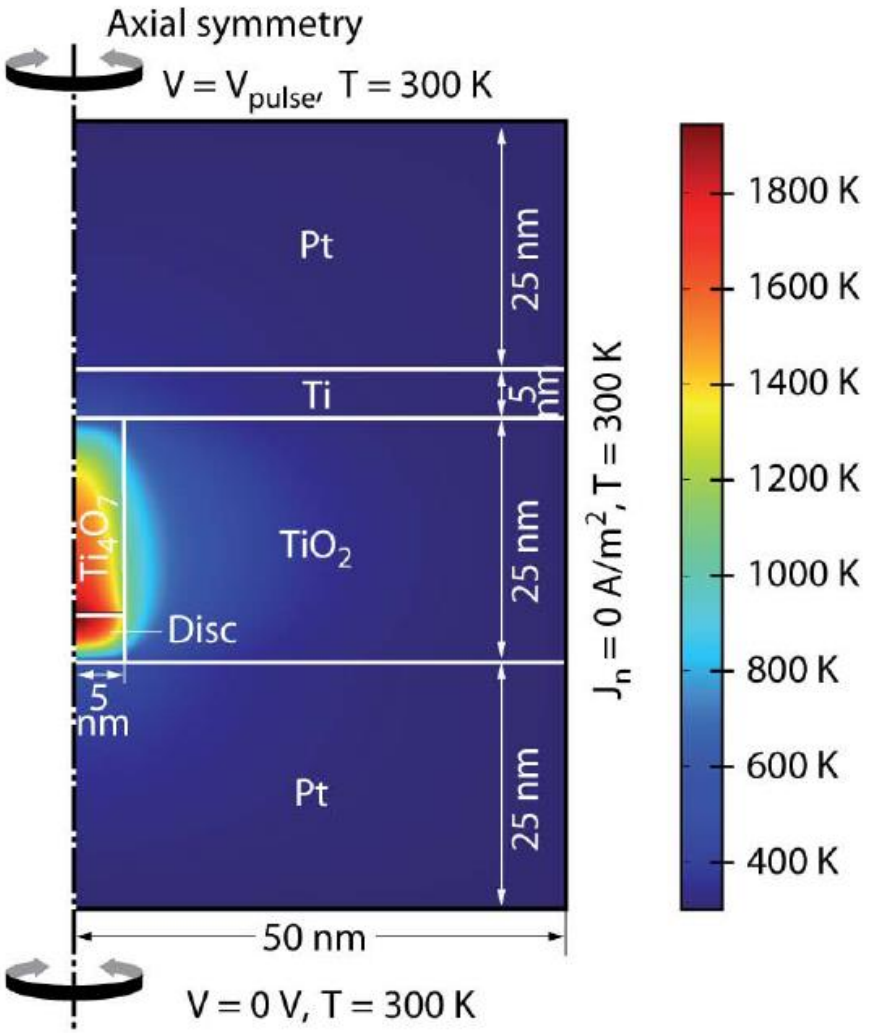
- Modeling of resistive switching with different compliance current
- Affects number of filaments and the size of the filament

Scalability

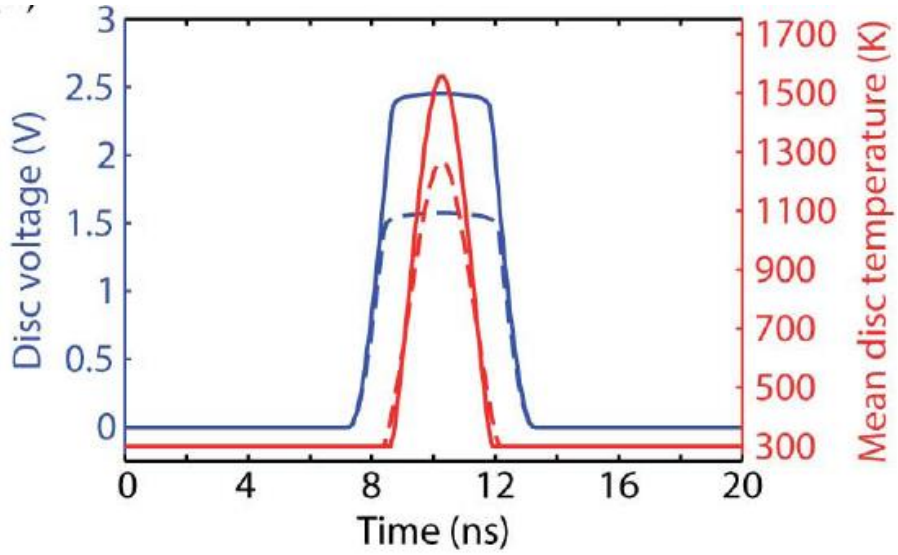
- Conductive filament critical size
  - Switching mechanism
  - Endurance
- Better on/off ratio
- Reduced variability in operations



Switching Speed

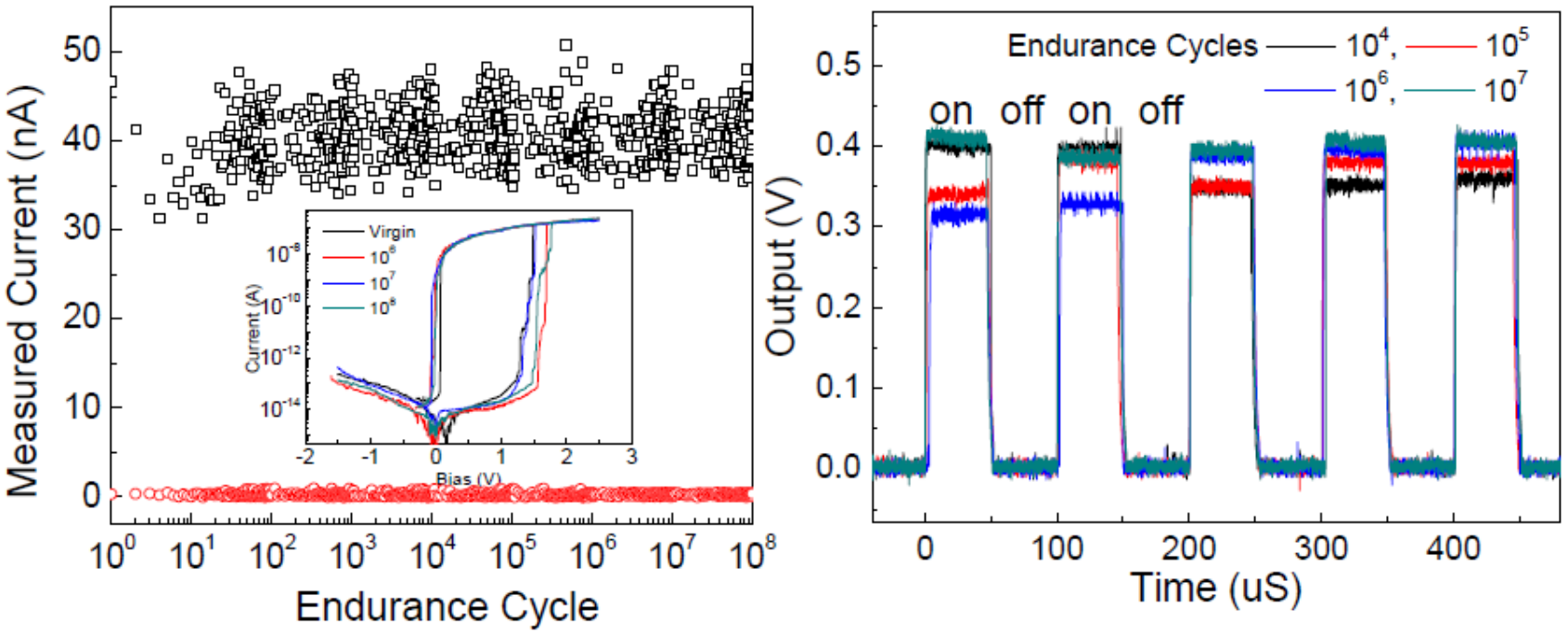


- Benchmark: DRAM write/erase time < 10/10 ns
- Pt/Ti/TiO2/Pt cross-point
  - 1 ns rise/fall and 3 ns plateau



Hermes et al., IEEE EDL, 2011

Endurance

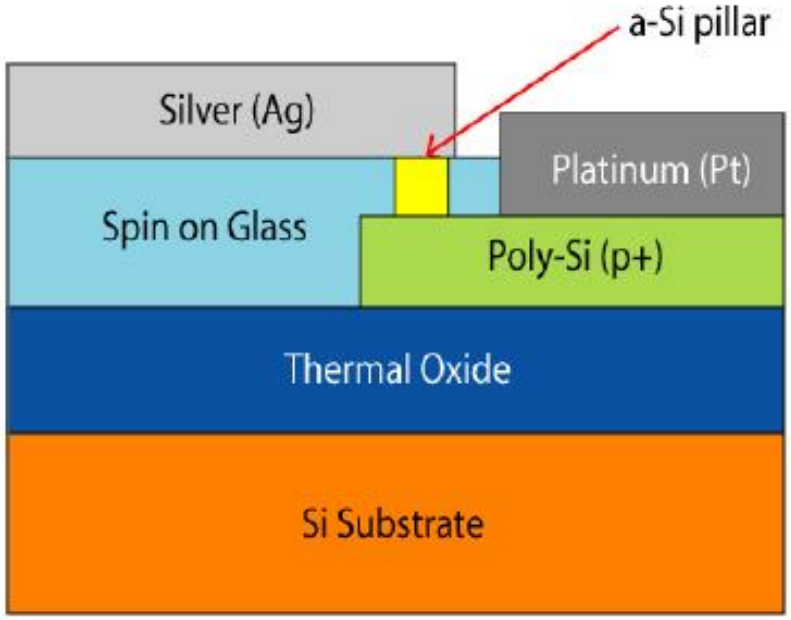


Jo et al., Nano Lett., 2008

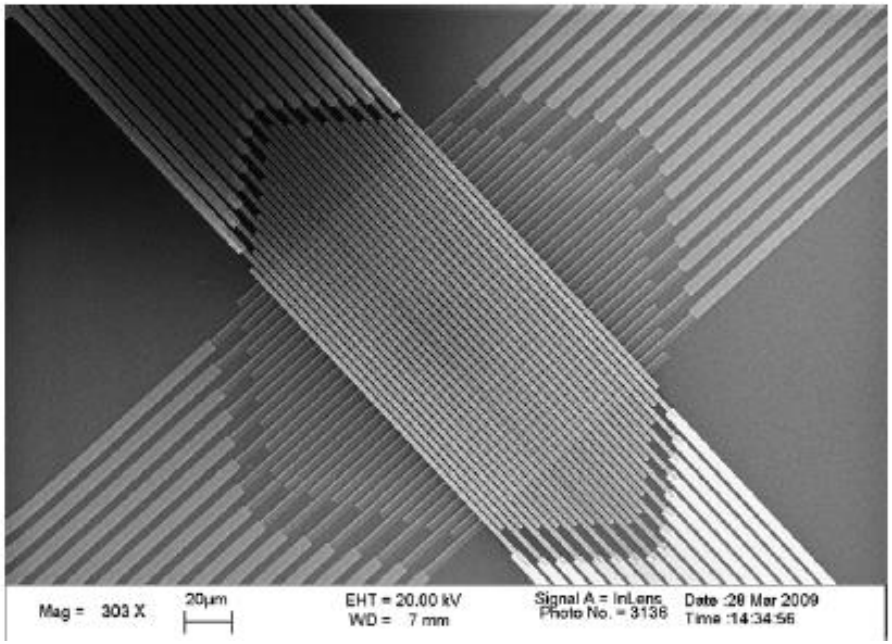
- 10^8 write/erase cycles
- 10^6 on/off ratio
- Endurance depends on device dimensions

RRAM Device Structure Pillar vs. Crossbar

Pillar structure



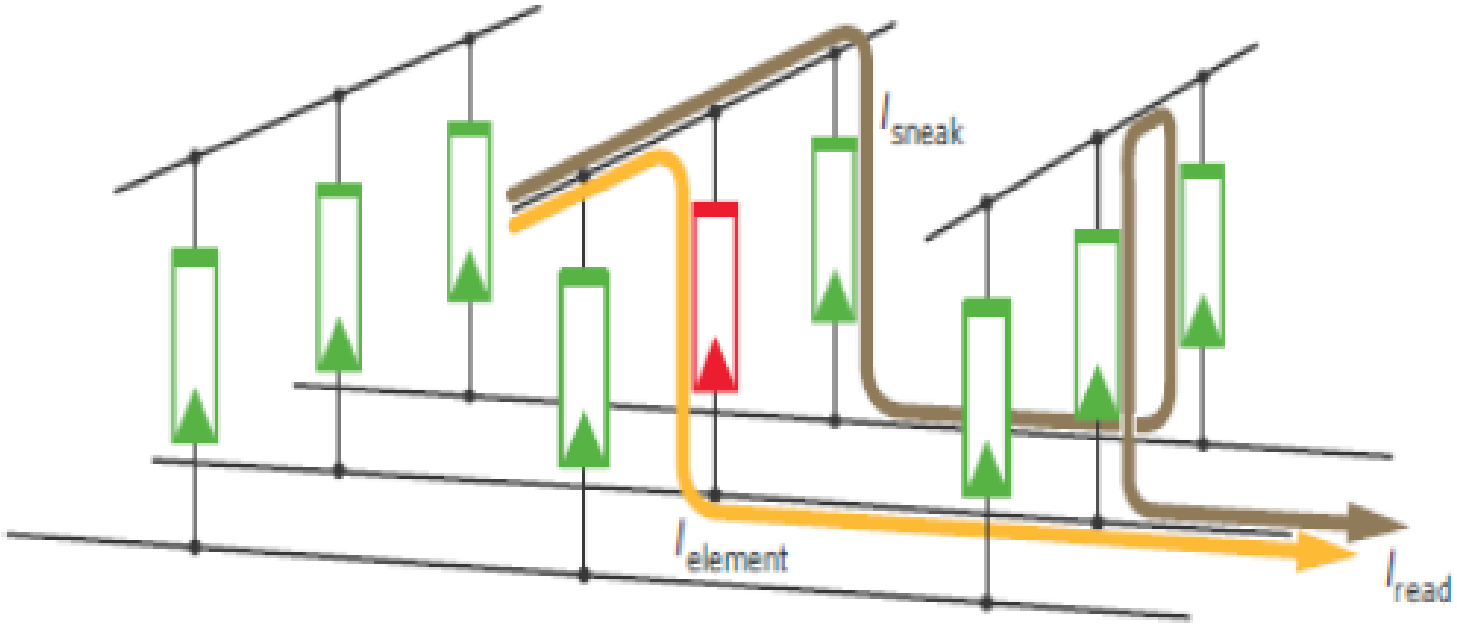
Crossbar array



Jo et al., Nano Lett., 2008

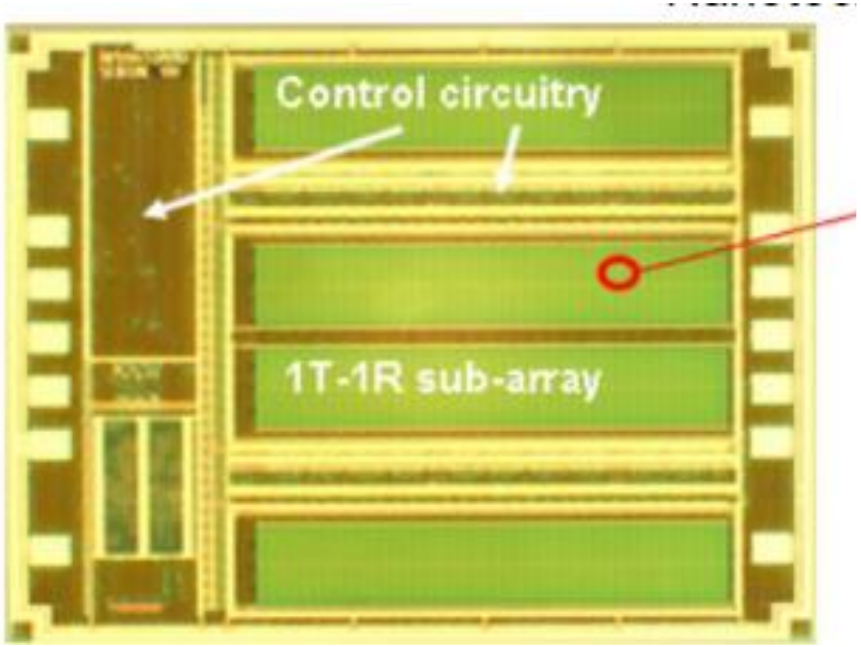
- Pillar vs crossbar
- Pillar is easier to fabricate;
- crossbar has better density and offers random access

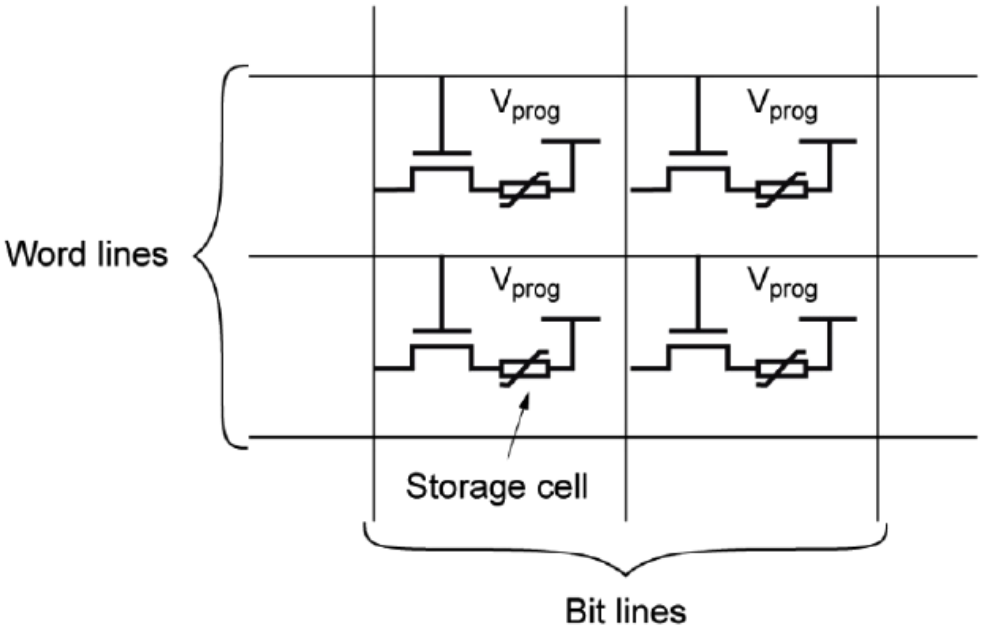
Sneak Path and Selection Device



- Sneak path in crossbar arrays
- Selection device is required
- 1 transistor 1 resistor (1T1R)
- 1 diode 1 resistor (1D1R), more compact

1T1R Array Demonstration



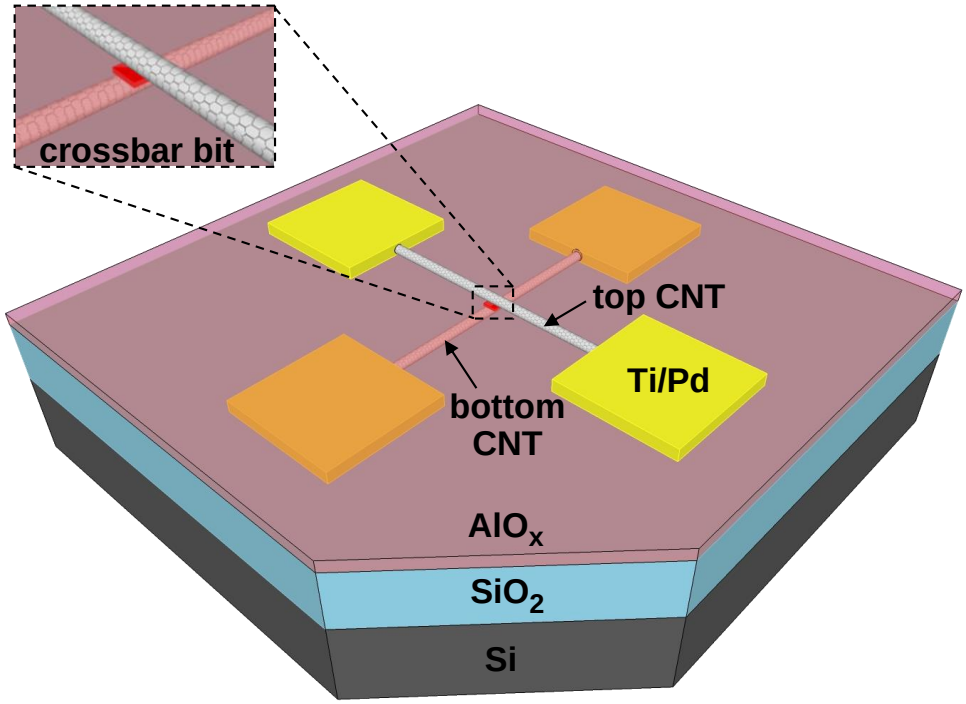


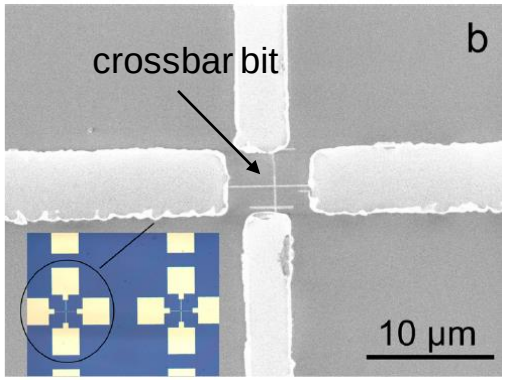
- 1T1R – 1 transistor and 1 RRAM cell
- Prevents sneak path
- Good density

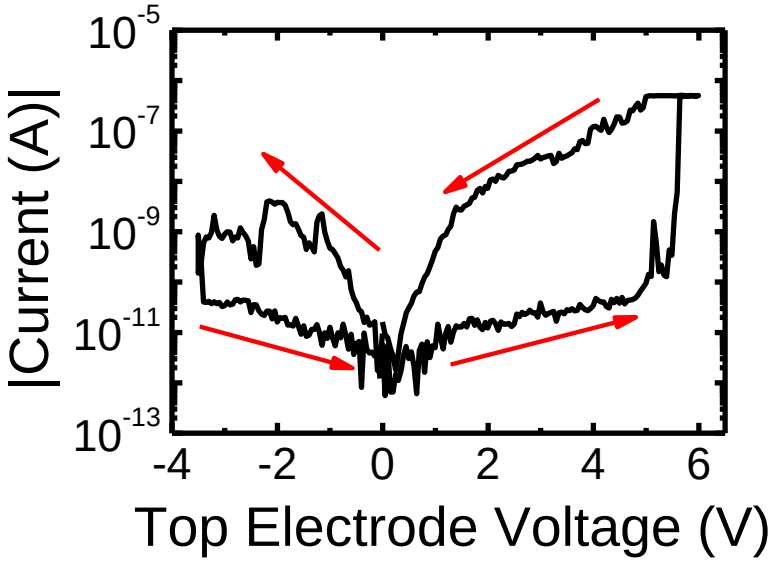
Valov et al., Nanotechnology, 2011

CNT Crossbar Devices

C.-L. Tsai, **F. Xiong**, E. Pop, M. Shim, *ACS Nano* **7**, 5360-5366 (2013)

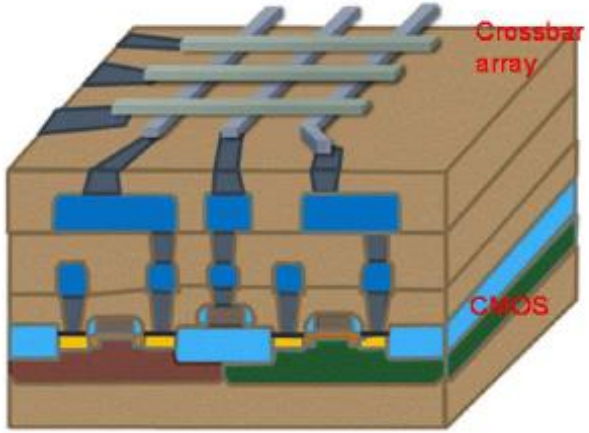


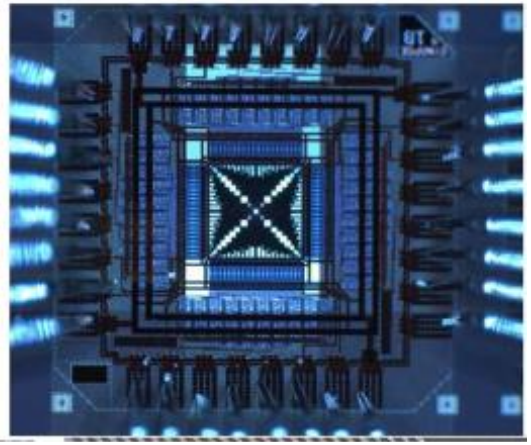


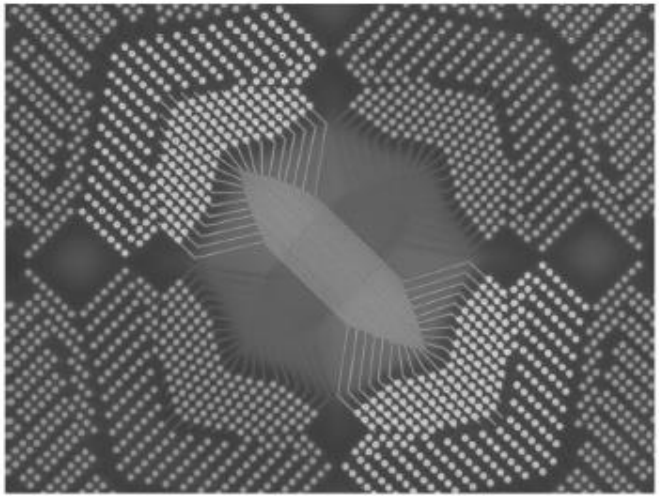


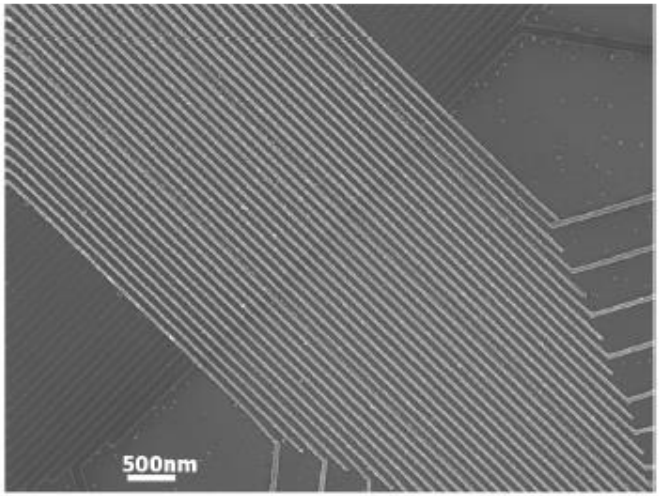
- CNT crossbar electrodes ~ 2 nm^2
- High performance and low power

Crossbar Array from Crossbar Inc.







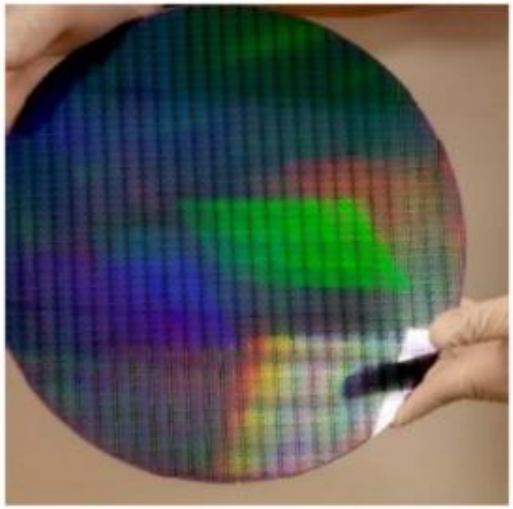


- RRAM crossbar array: 100 nm pitch
- 10 Gbits/cm^2

Kim et al., Nano Lett., 2012

Towards Commercialization

- Crossbar Inc. founded in 2010 with $85 M funding so far
- Commercial products offered in 2016 with 40 nm CMOS
- CMOS compatible
- 3D stackable with low thermal budget process



Crossbar

Samsung Vertical 3D

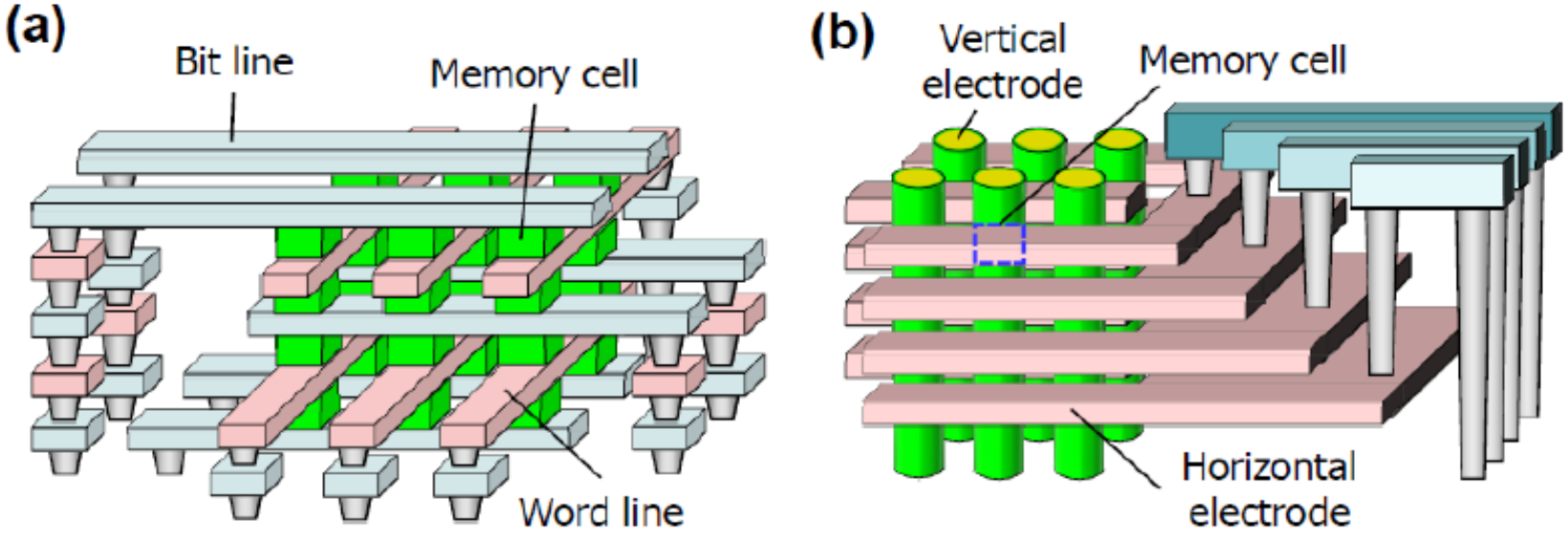
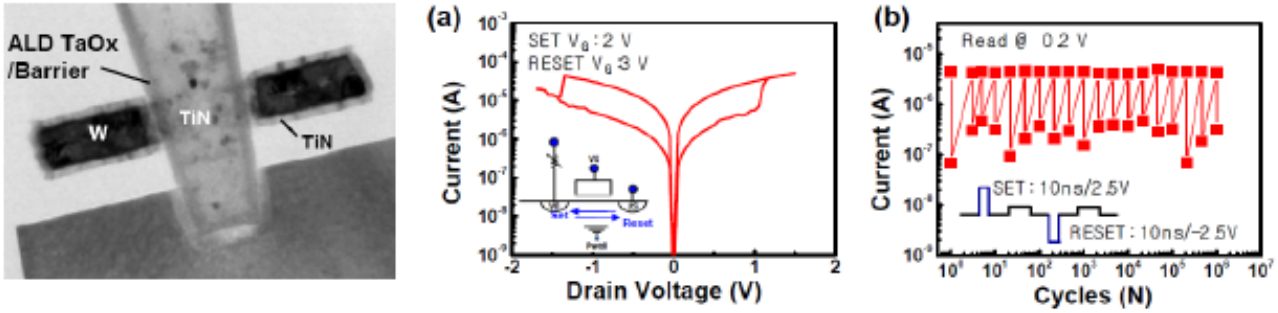
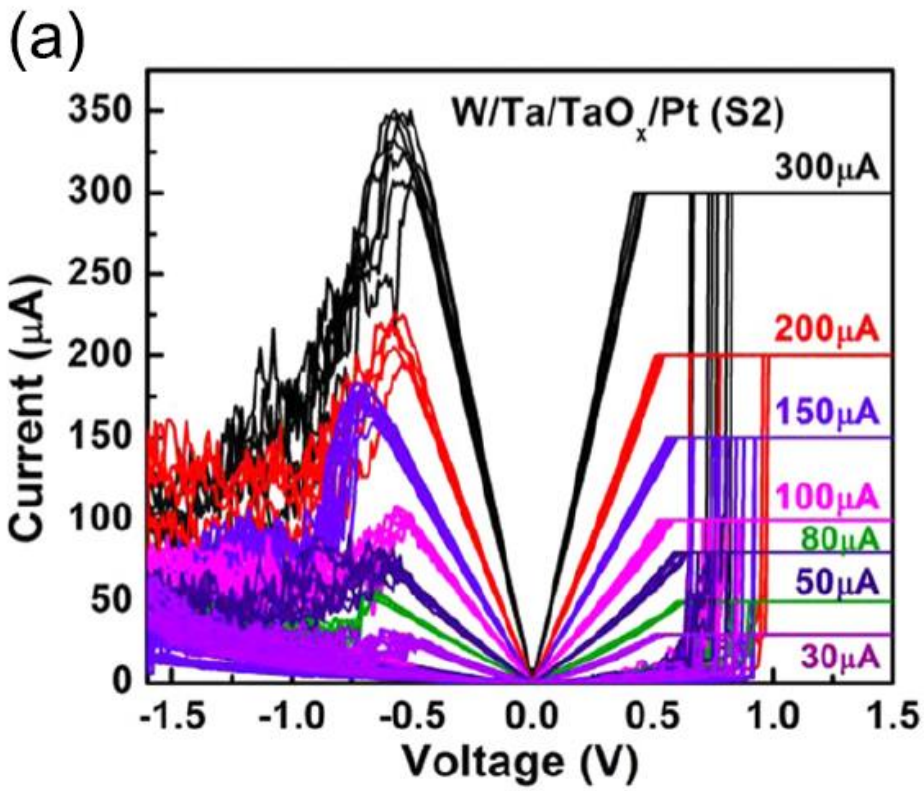


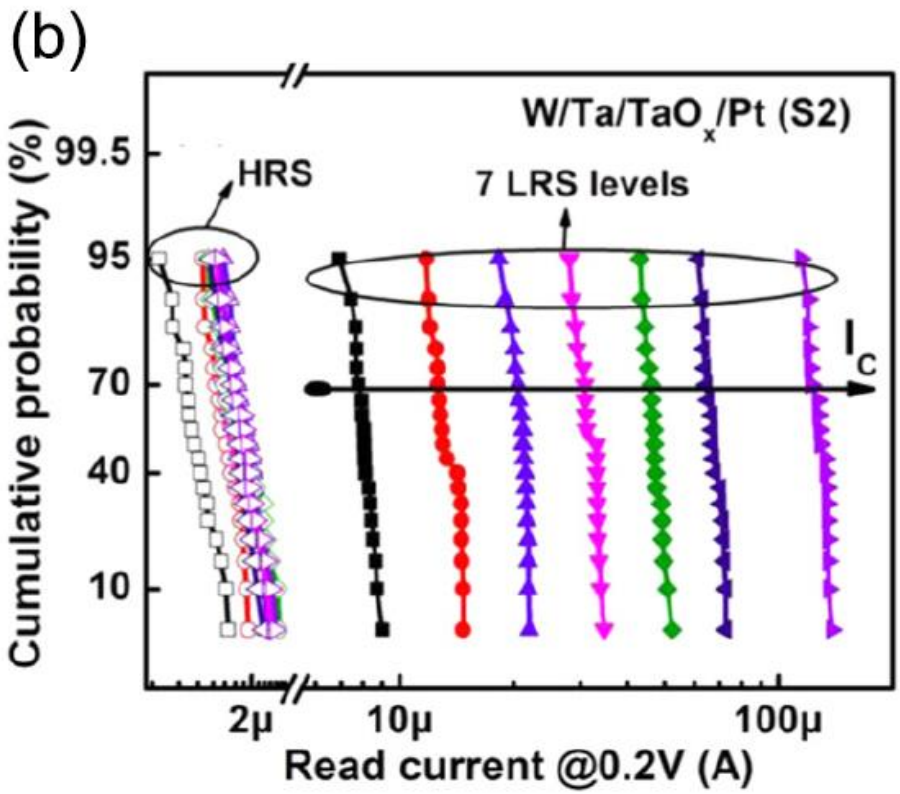
Fig. 1 Schematic drawings of (a) 3D X-point ReRAM, (b) Vertical ReRAM



- Samsung claims vertical RRAM is more cost effective — Baek, IEDM 2011, 31.8
- Prototype cell works with a vertical structure (TaOx-based)

Multi-Level Cell

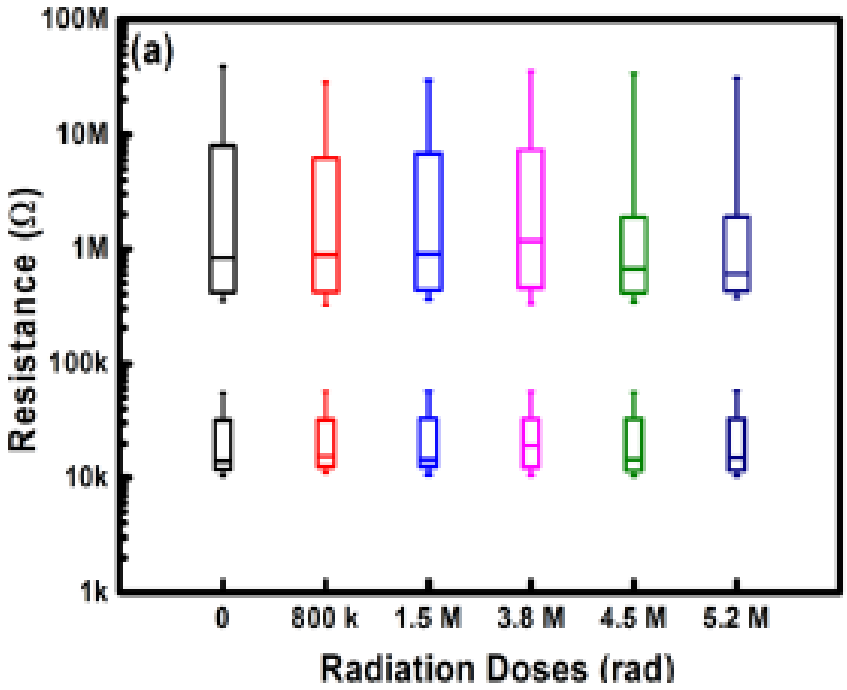


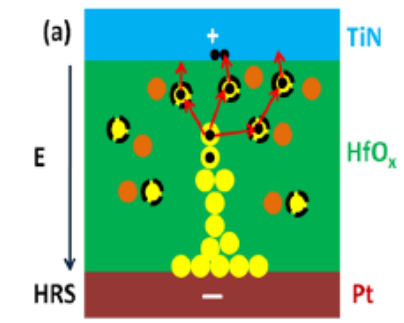


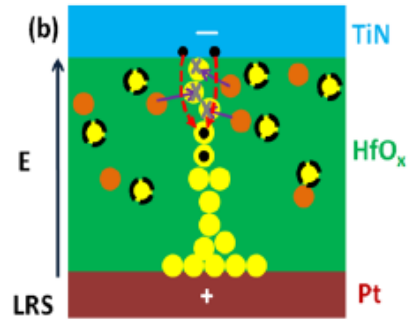
- Multi-level cell (MLC) → higher density
- 8 levels → 3 bit per cell
- Stochastic process makes uniformity more challenging

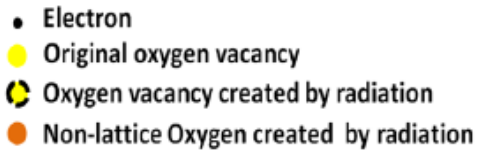
Radiation Resistant

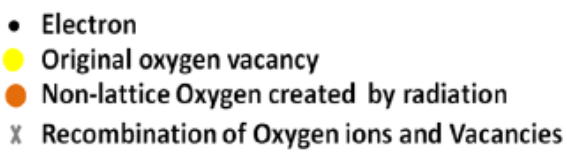
- RRAM is not charge-based (DRAM and flash)
- Radiation resistant → good for military and space applications
- HRS (HfO_x) may decrease slightly upon radiation











Fang et al., APL, 2014