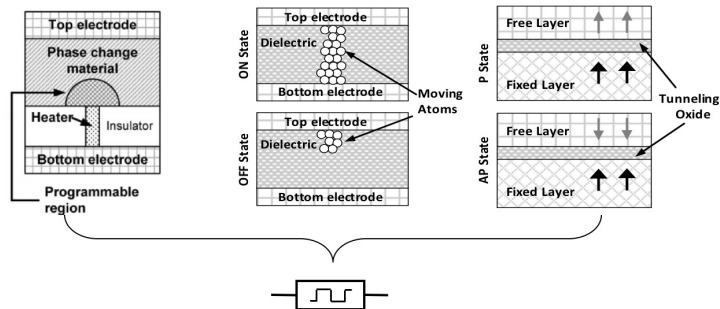
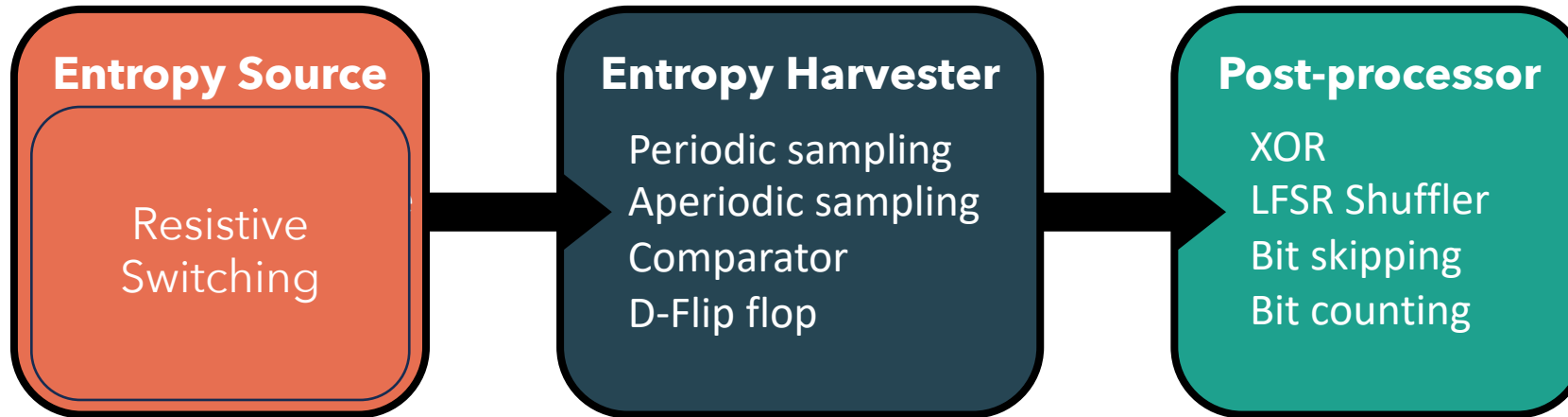


---

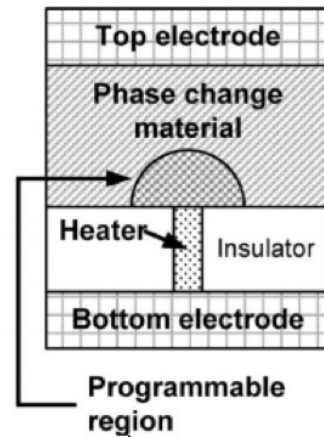
# Generating Random Numbers with Emerging Memory Devices

Elena Ioana Vătăjelu

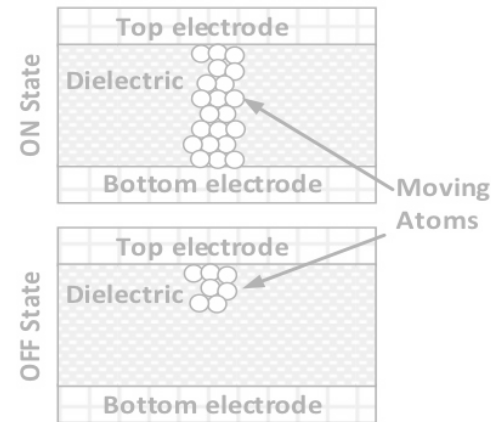
CR CNRS



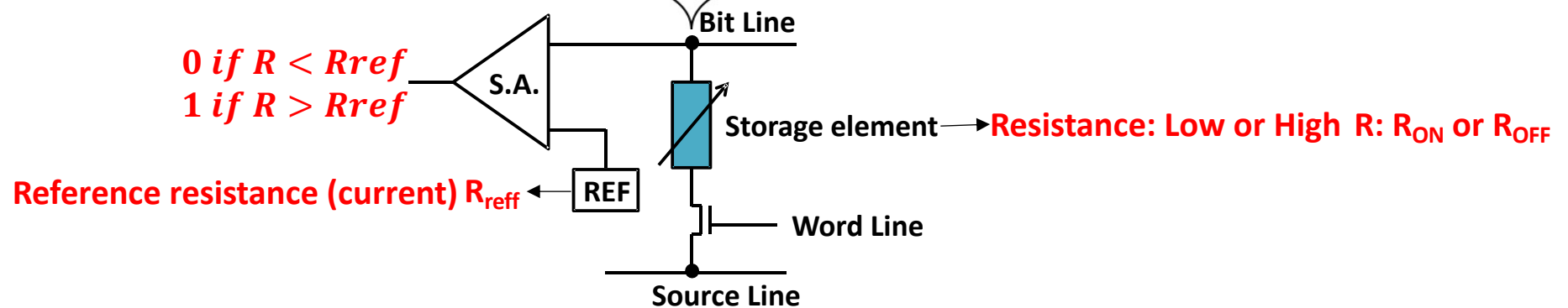
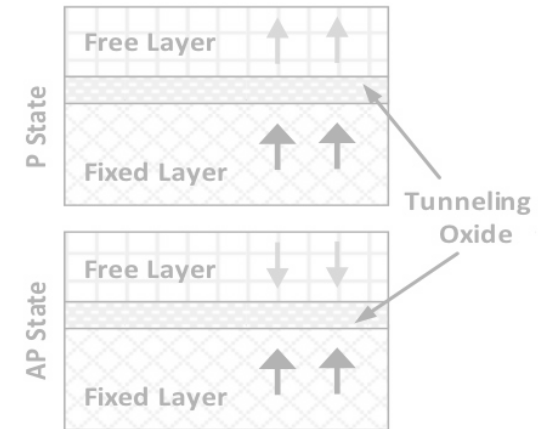
## Phase Change Memory

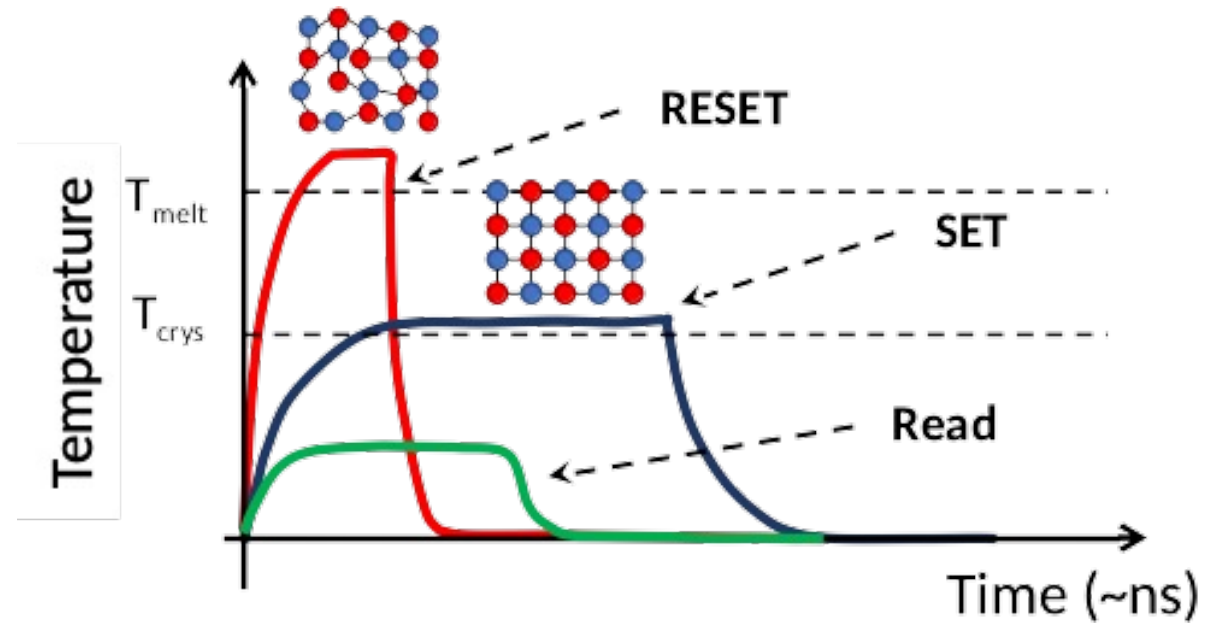
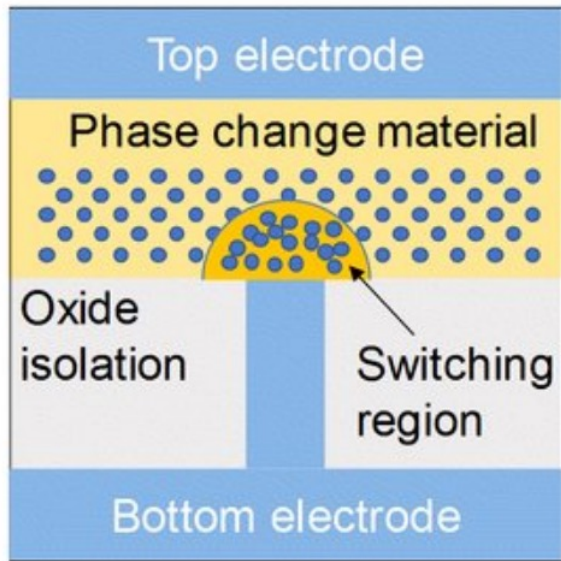


## Resistive RAM



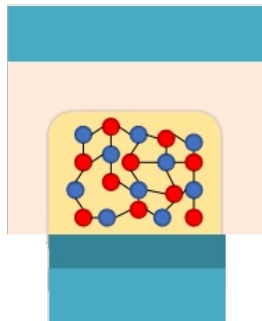
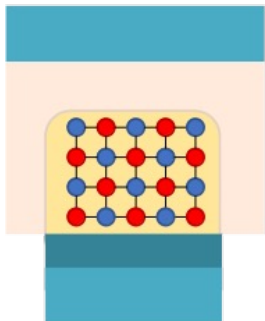
## Spin-Transfer Torque MRAM





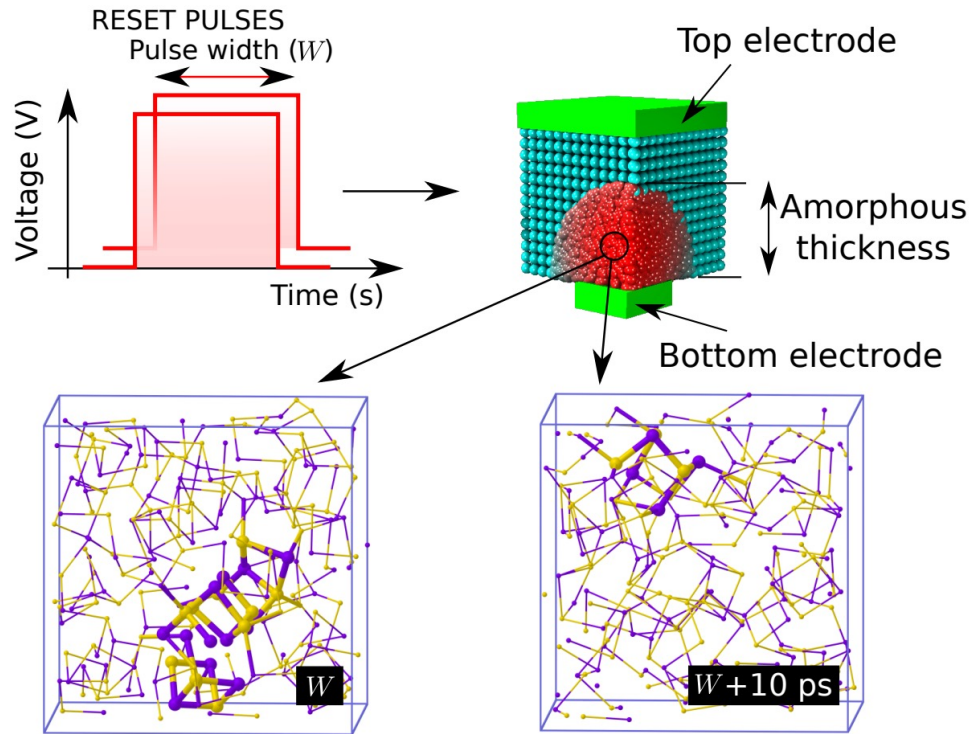
Crystalline State

Amorphous State



- ◆ Electrode
- ◆ Heater
- ◇ Chalcogenide Glass (GeSbTe)
- ◇ Programmable Volume

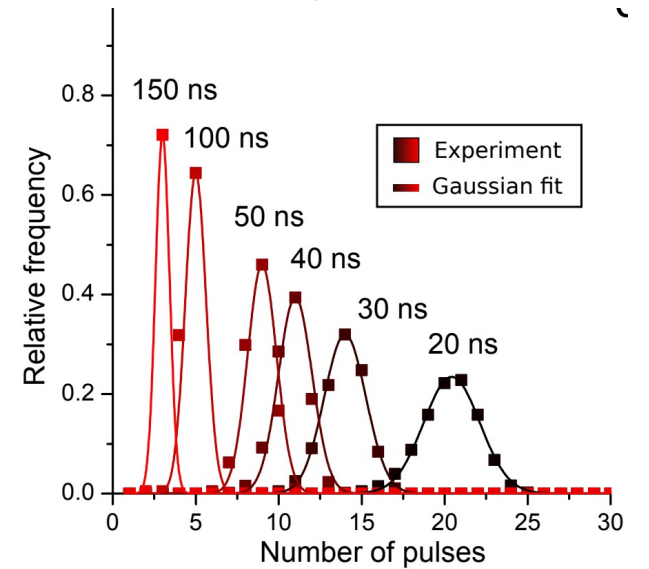
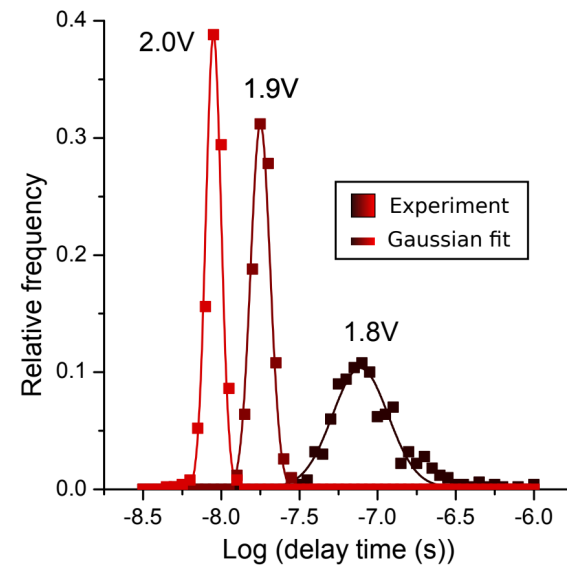
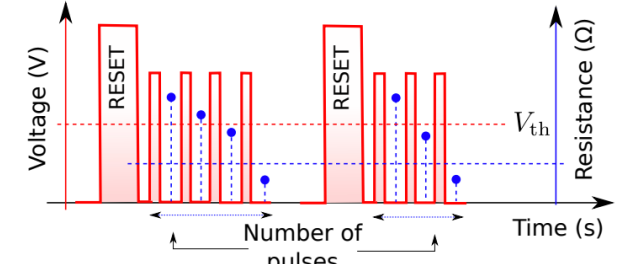
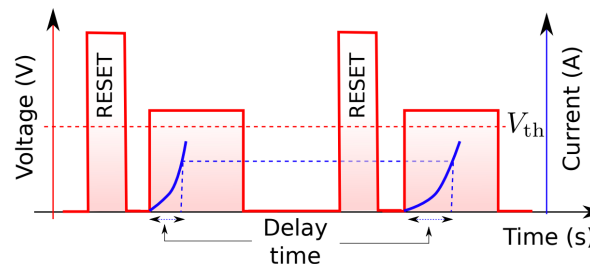
# PCM (Phase Change Memory) - Stochasticity -



Cycle-to-cycle variation of the thickness and atomic configuration of the amorphous state

## Threshold Switching

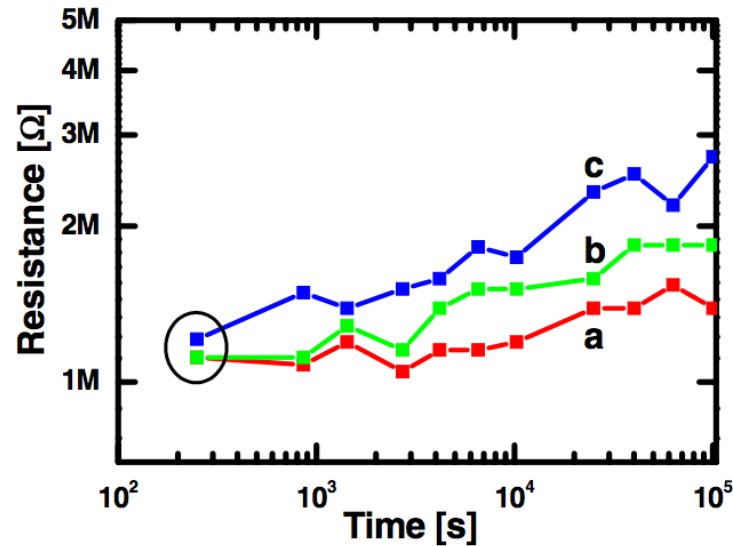
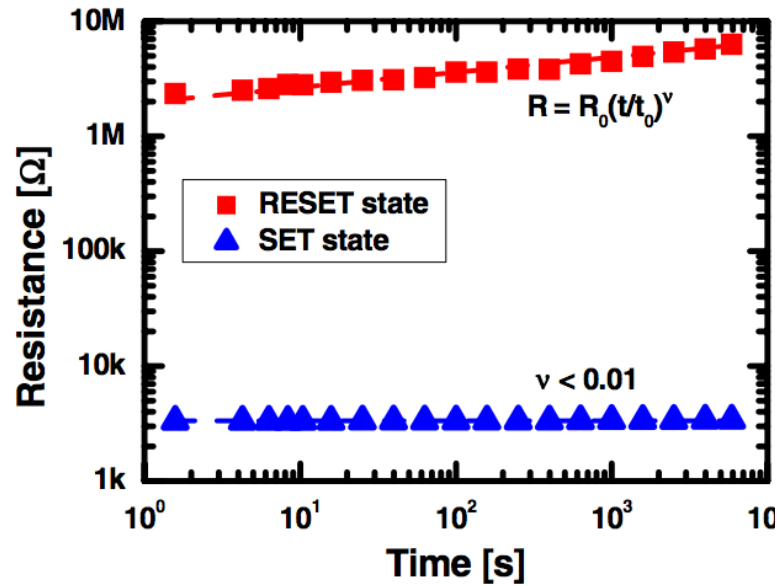
## Memory Switching



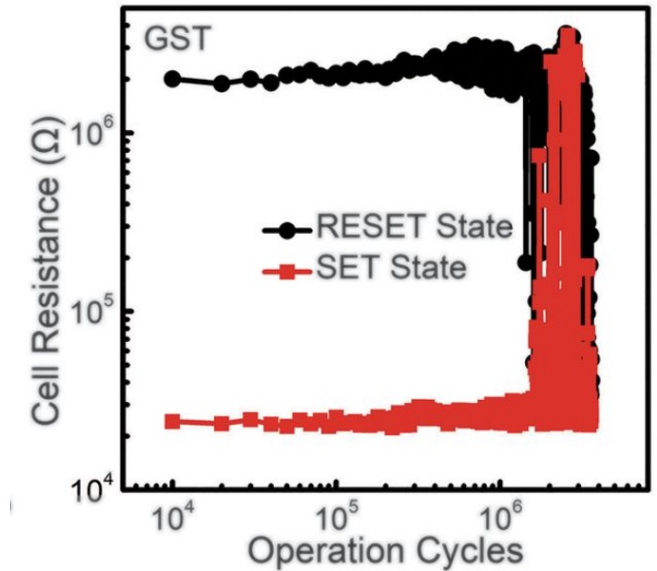
# PCM (Phase Change Memory)

## - Issues -

### Resistance Drift



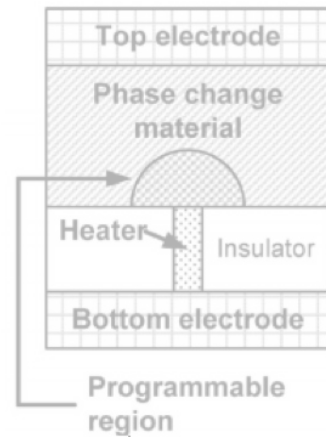
### Cycling endurance



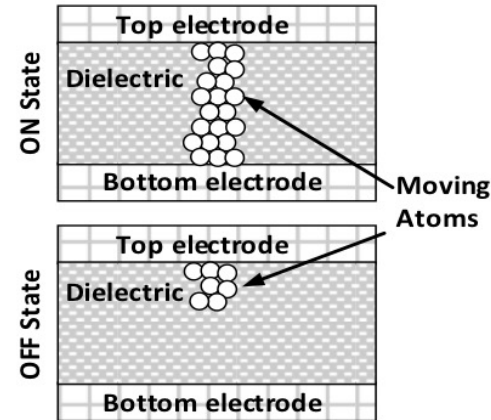
Keyuan Ding et al., Phase-change heterostructure enables ultralow noise and drift for memory operation. *Science*, 366,210-215(2019)

Boniardi, Mattia et al. "Statistics of Resistance Drift Due to Structural Relaxation in Phase-Change Memory Arrays." *IEEE Transactions on Electron Devices* 57 (2010): 2690-2696.

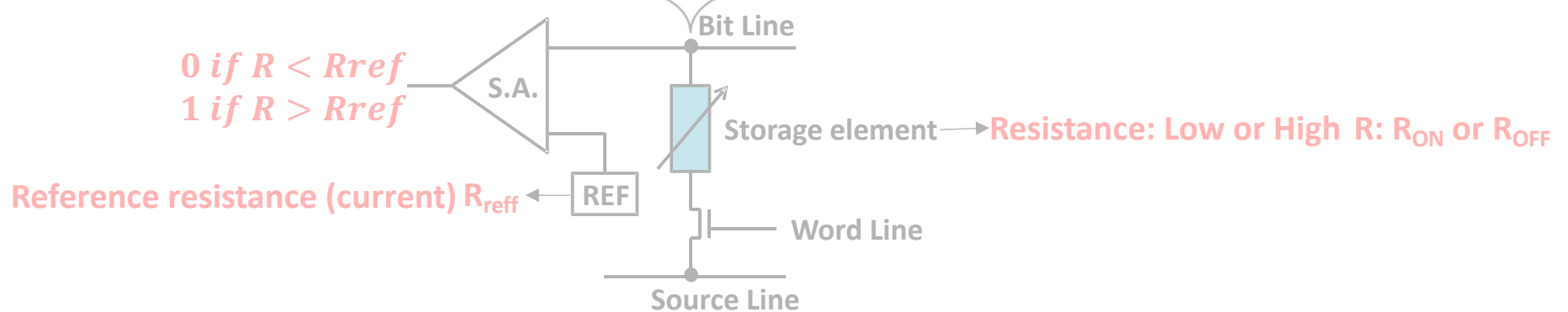
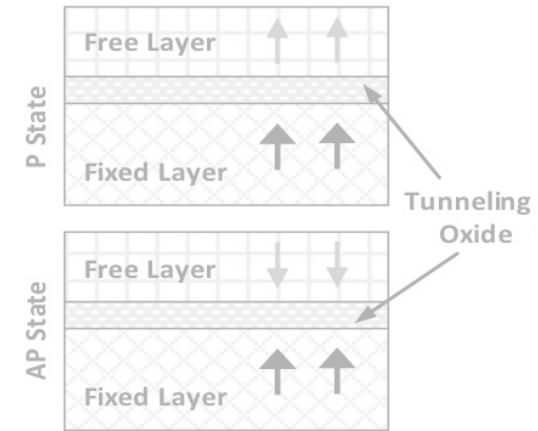
Phase Change Memory

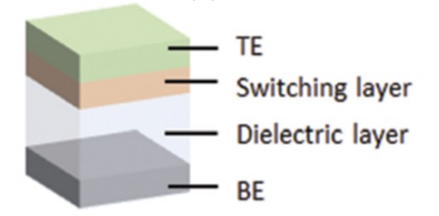
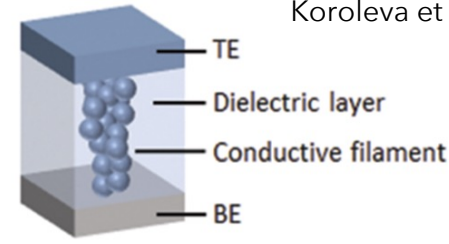
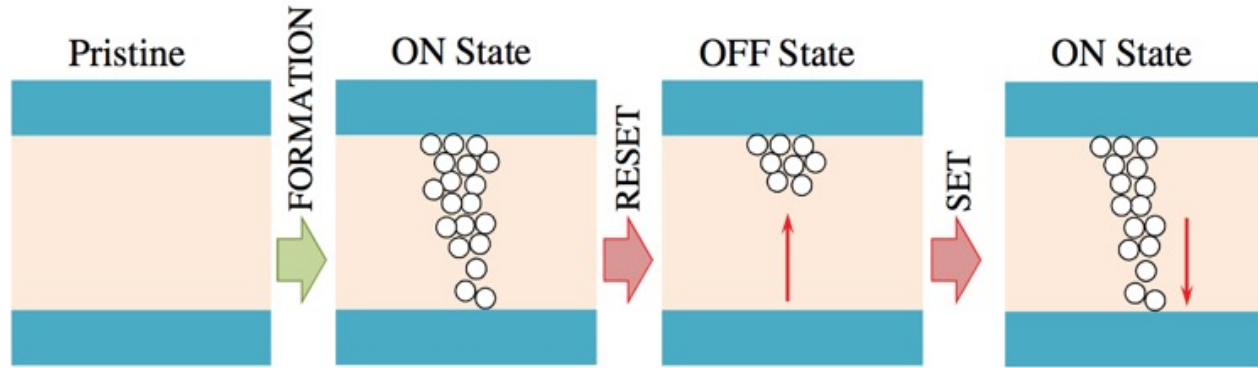


Resistive RAM

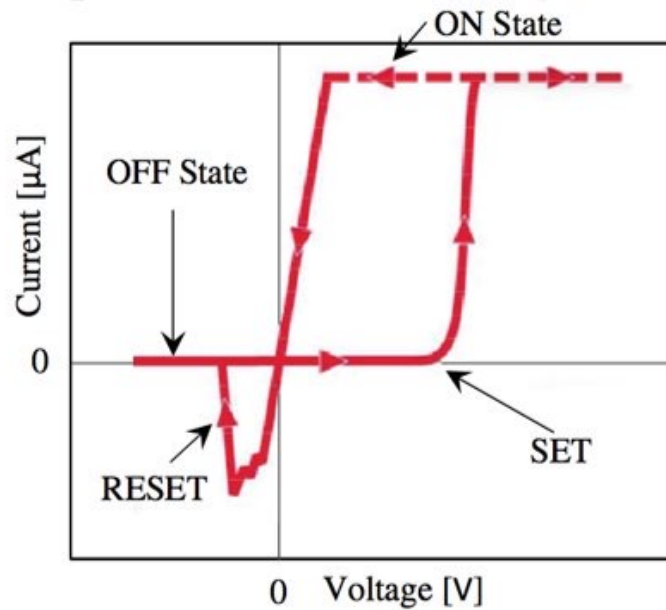


Spin-Transfer Torque MRAM

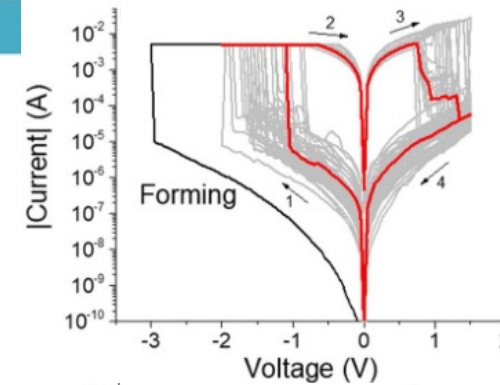




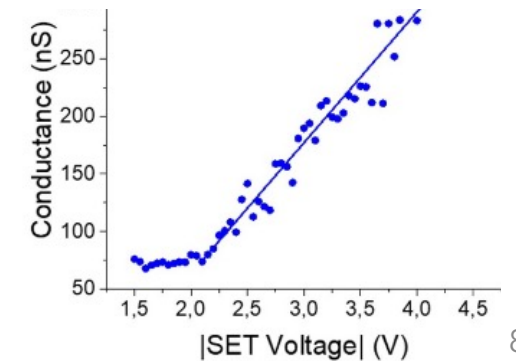
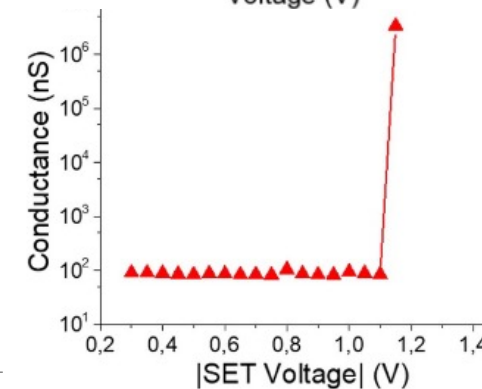
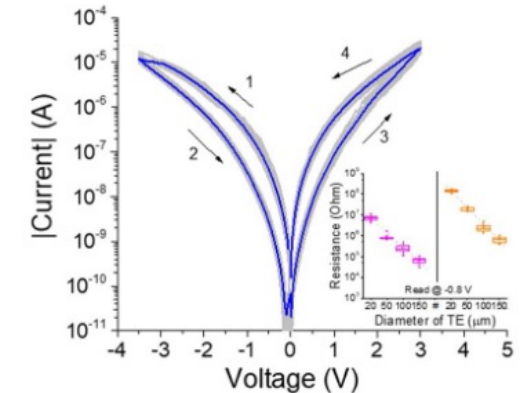
Koroleva et al 2021 J. Phys. D: Appl. Phys.54 504004



Filamentary switching RRAM

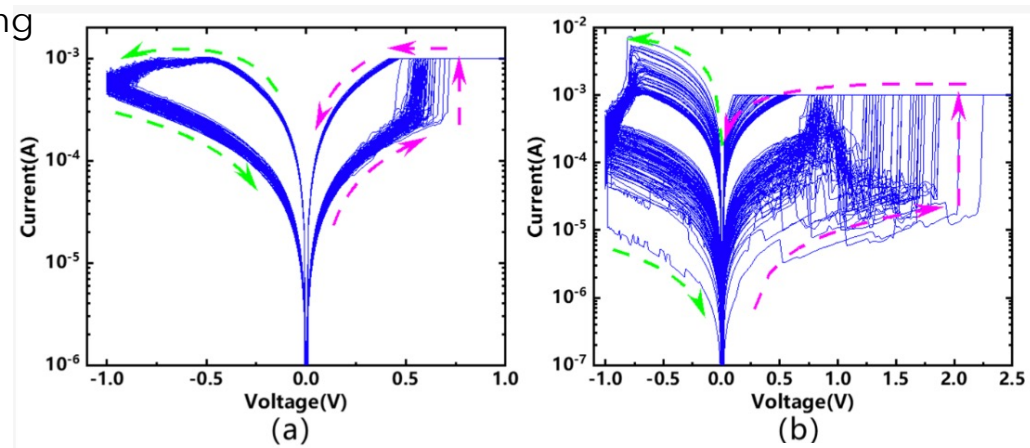
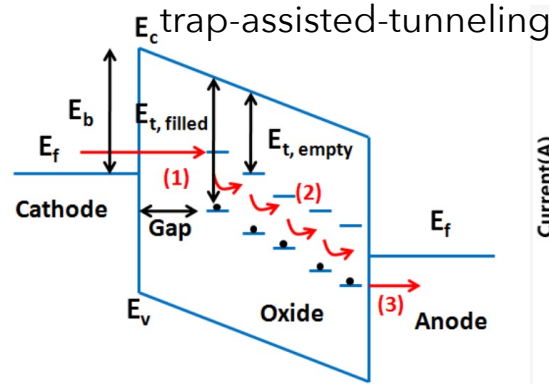
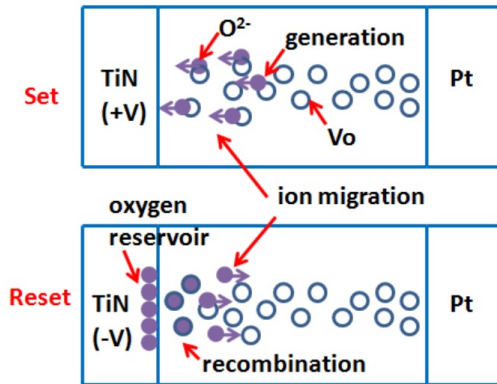


Uniform switching RRAM

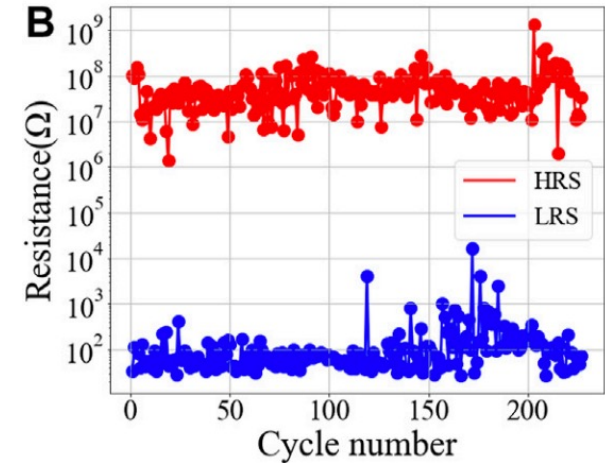




# RRAM (Resistive Memory) - Stochasticity -



Stochastic process of moving atoms in a dielectric due to discrete displacements ('hopping') of atoms which will occur with a certain probability



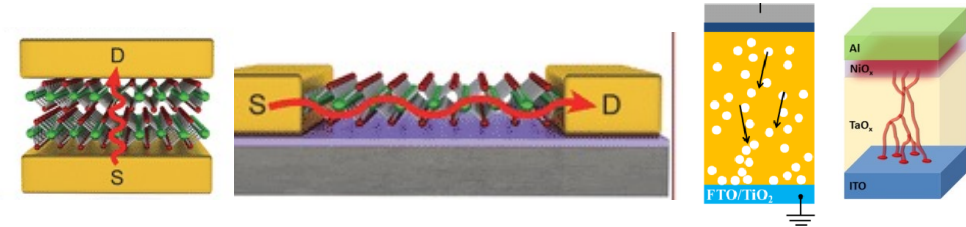
Huang, Yifu et al. ReSe2-Based RRAM and Circuit-Level Model for Neuromorphic Computing. *Frontiers in Nanotechnology*. 3. 10.3389/fnano.2021.782836.

S. Yu, et al, "On the stochastic nature of resistive switching in metal oxide RRAM: Physical modeling, monte carlo simulation, and experimental characterization," 2011 IEDM

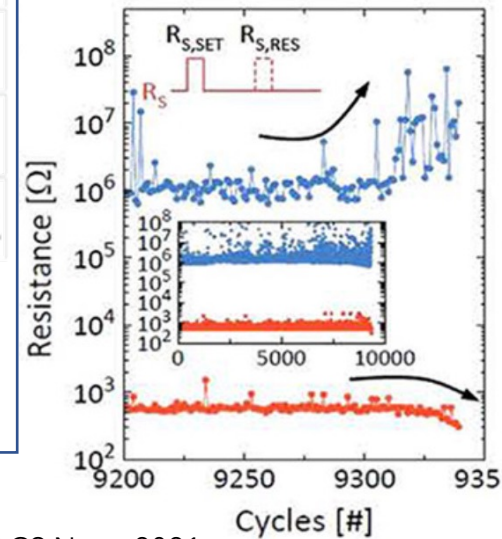
# RRAM (Resistive Memory) - Issues -

<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="width: 20px; height: 20px; background-color: #f4a460; border: 1px solid black;"></div> <p>Corresponding binary oxide with bi-stable resistive switching</p> </div> <div style="display: flex; justify-content: space-around; align-items: center; margin-top: 10px;"> <div style="width: 20px; height: 20px; background-color: #00a0c9; border: 1px solid black;"></div> <p>Metal used for electrodes</p> </div>																	
1 IA 1A	2 IIA 2A	3	4	5	6	7	8	9	10	11	12	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008	2 He Helium 4.003	3 Li Lithium 6.941	4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.796
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine 209	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [266]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [285]	113 Uut Ununtrium [288]	114 Fl Flerovium [289]	115 Uup Ununpentium [293]	116 Lv Livermorium [293]	117 Uus Ununseptium [294]	118 Uuo Ununoctium [294]
89 La Lanthanum 138.905	90 Ce Cerium 140.116	91 Pr Praseodymium 140.908	92 Nd Neodymium 144.242	93 Pm Promethium [145]	94 Sm Samarium 150.36	95 Eu Europium 151.964	96 Gd Gadolinium 157.25	97 Tb Terbium 158.925	98 Dy Dysprosium 162.500	99 Ho Holmium 164.930	100 Er Erbium 167.259	101 Tm Thulium 168.934	102 Yb Ytterbium 173.055	103 Lu Lutetium 174.967			
90 Ac Actinium 227	91 Th Thorium 232	92 Pa Protactinium 231	93 U Uranium 238	94 Np Neptunium 237	95 Pu Plutonium 244	96 Am Americium 243	97 Cm Curium 247	98 Bk Berkelium 247	99 Cf Californium 251	100 Es Einsteinium [252]	101 Fm Fermium 257	102 Md Mendelevium 258	103 No Nobelium 259	104 Lr Lawrencium [262]			

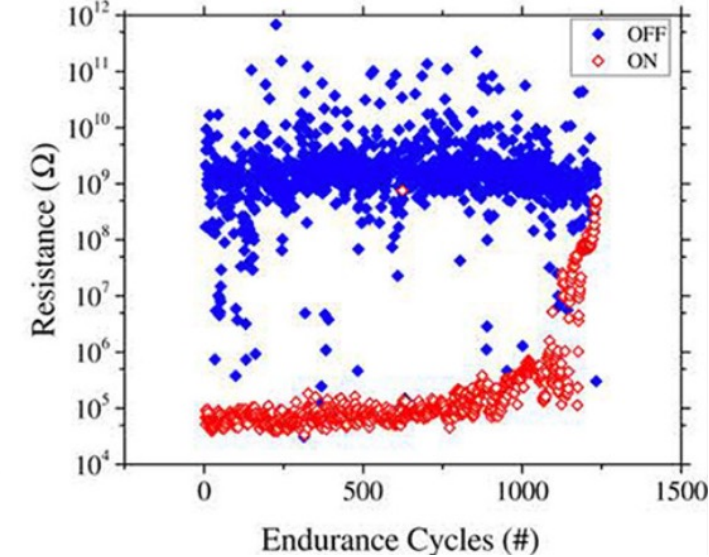
## Versatility



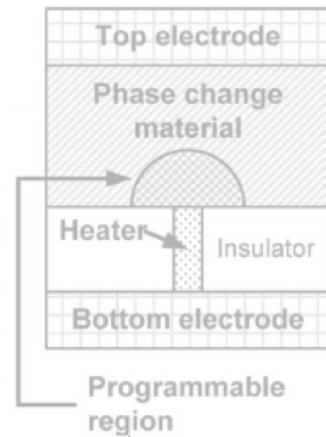
## Resistance Drift



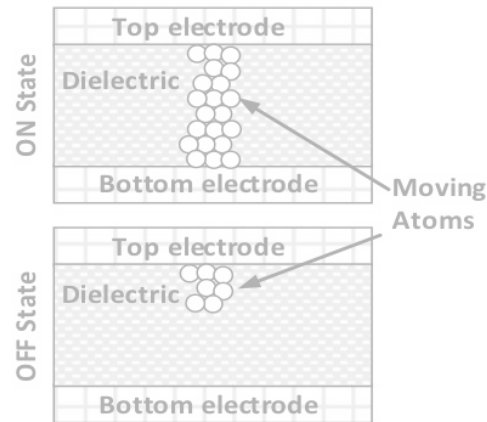
## Cycling Endurance



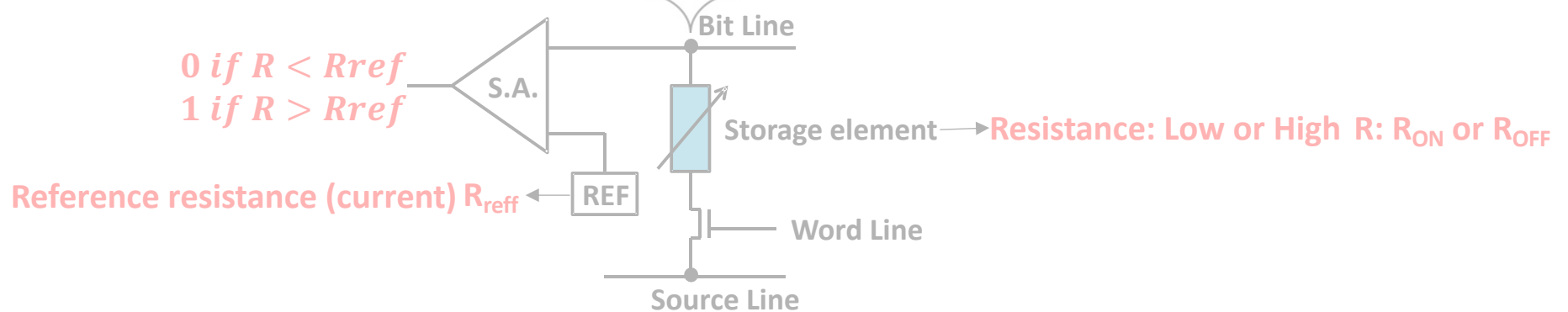
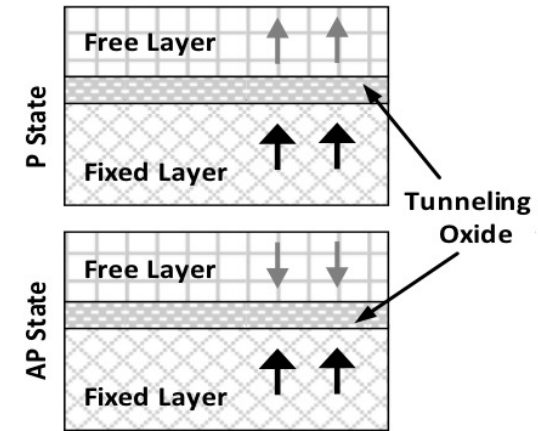
Phase Change Memory



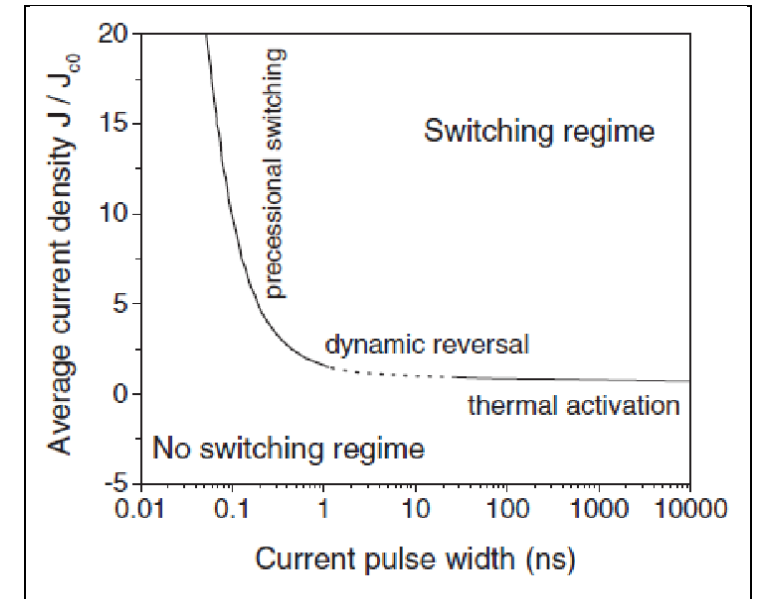
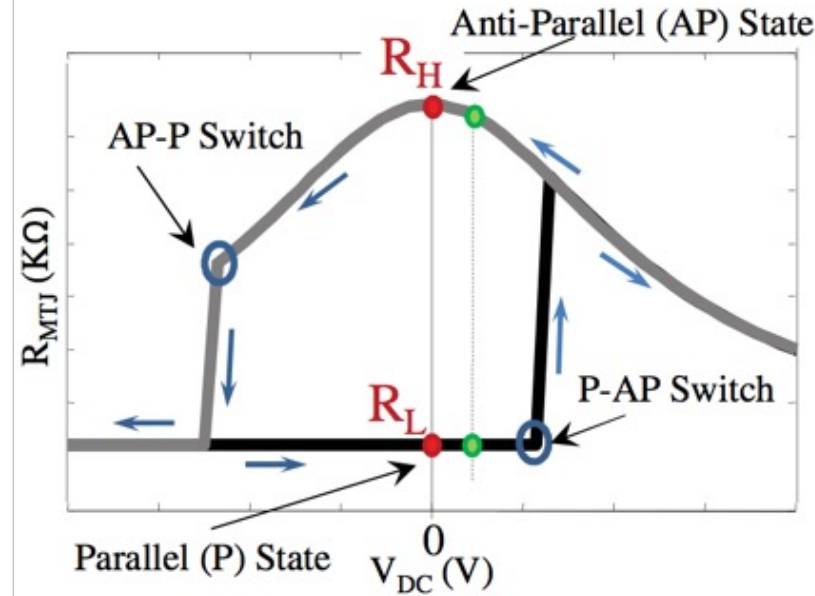
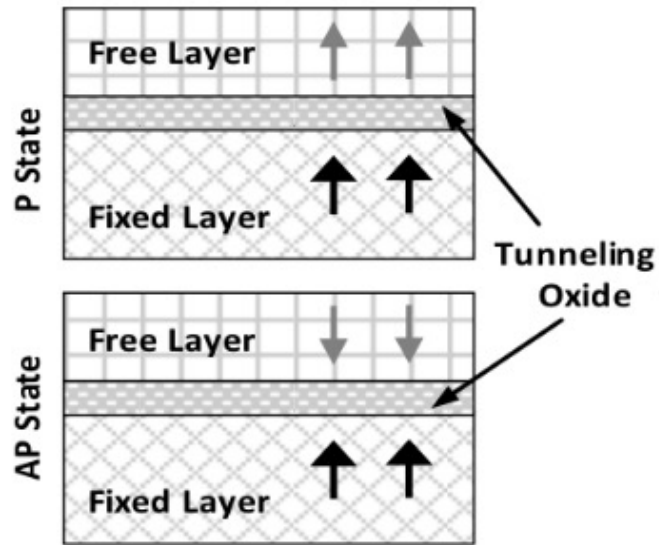
Resistive RAM



Spin-Transfer Torque MRAM



# TiMA MRAM (Magnetic Memory)



# MRAM (Magnetic Memory)

## - Stochasticity -

**Néel-Brown:** at finite temperature, there is a finite probability for the magnetization to flip and reverse its direction.

Néel-Brown model:

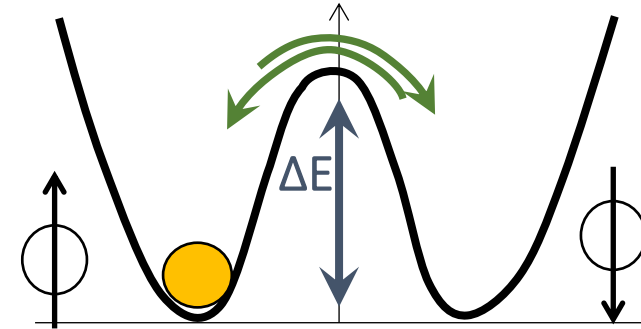
$$P(t) = \exp(-t/\tau) \rightarrow \text{source of entropy}$$

$$\tau = \tau_0 \exp(\Delta E/k_B T)$$

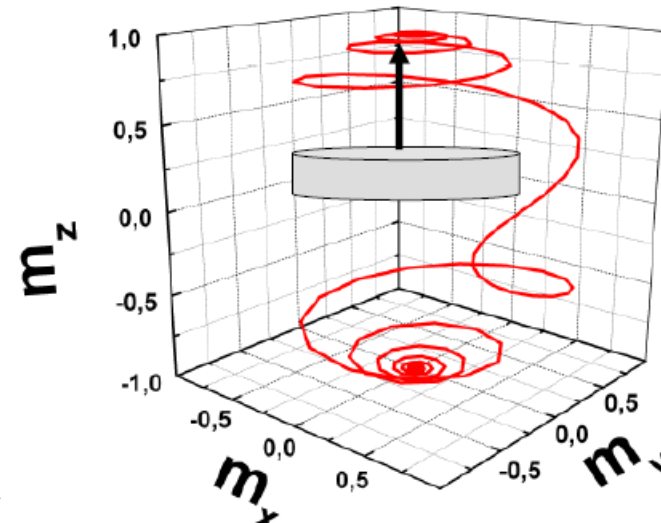
$$P_{wr} = \exp \left( \frac{-\pi^2 \cdot \Delta \cdot \left( \frac{I_w}{I_{c0}} - 1 \right) / 4}{\frac{I_w}{I_{c0}} \cdot \exp \left( 2 \cdot \alpha \cdot \gamma \cdot H_k \cdot \frac{I_w}{1 + \alpha^2} \cdot \frac{t_w}{1 + \alpha^2} \right) - 1} \right)$$

$$\Delta E = f(K, M) \cdot (A \cdot t_f / k_B T)$$

$K$  = anisotropy,  
 $M$  = demagnetization energy,  
 $A$  = area of free layer,  
 $t_f$  = thickness of free layer



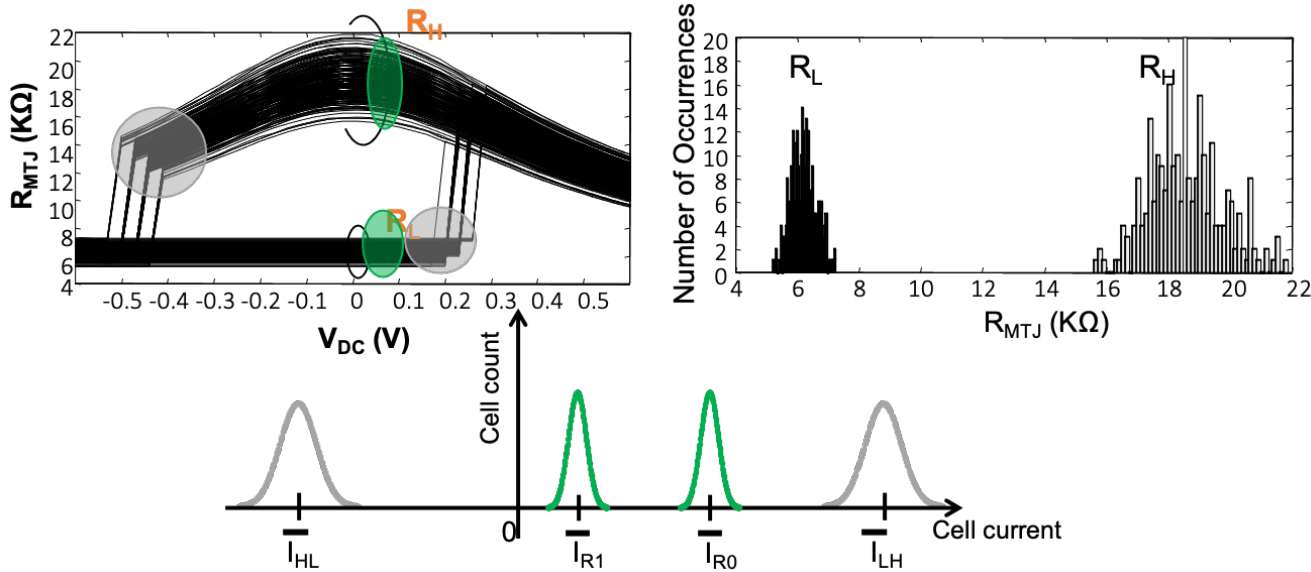
Digitalization



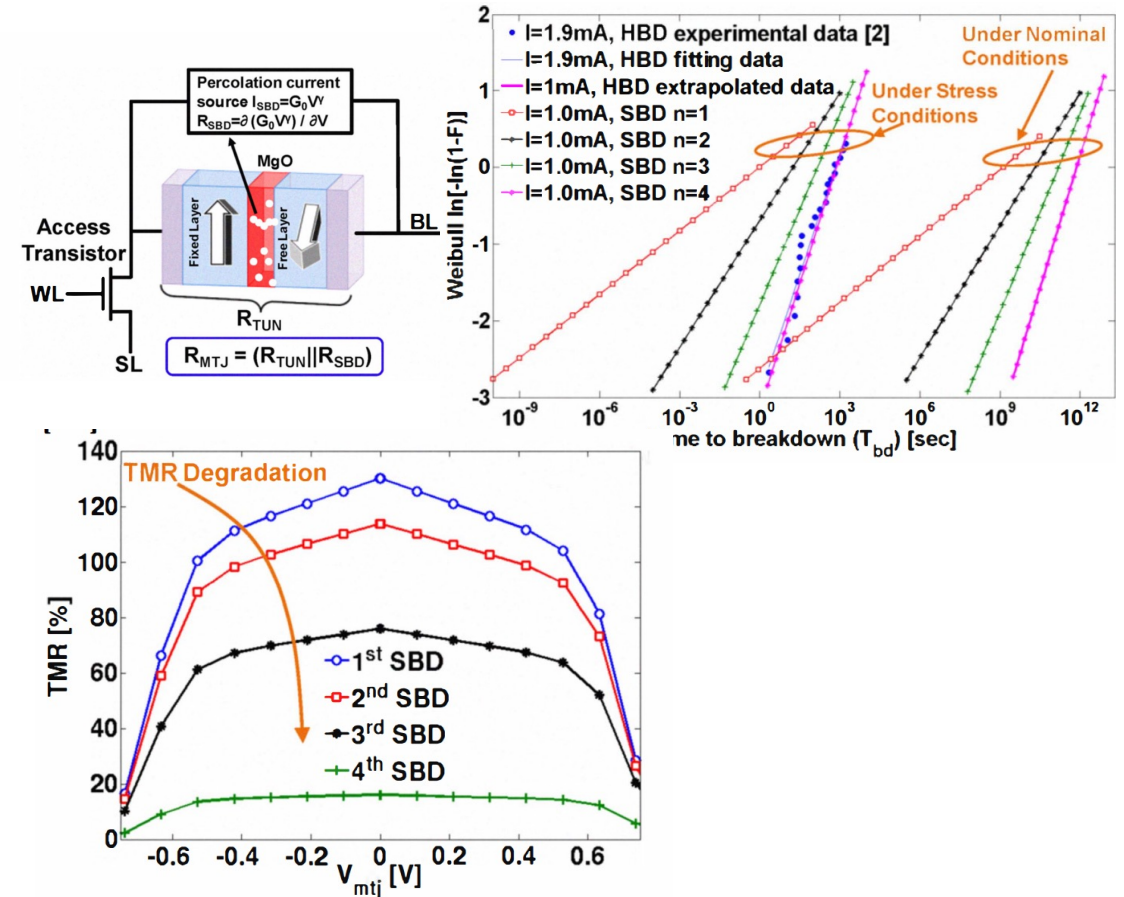
# MRAM (Magnetic Memory)

## - Issues -

### Process Variability



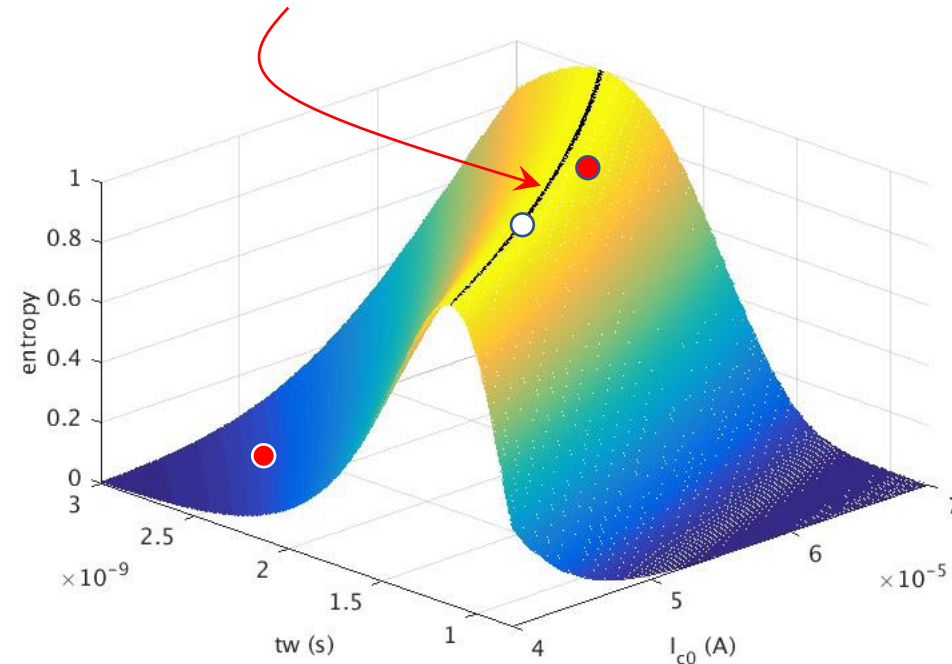
### Time-dependent Dielectric Breakdown



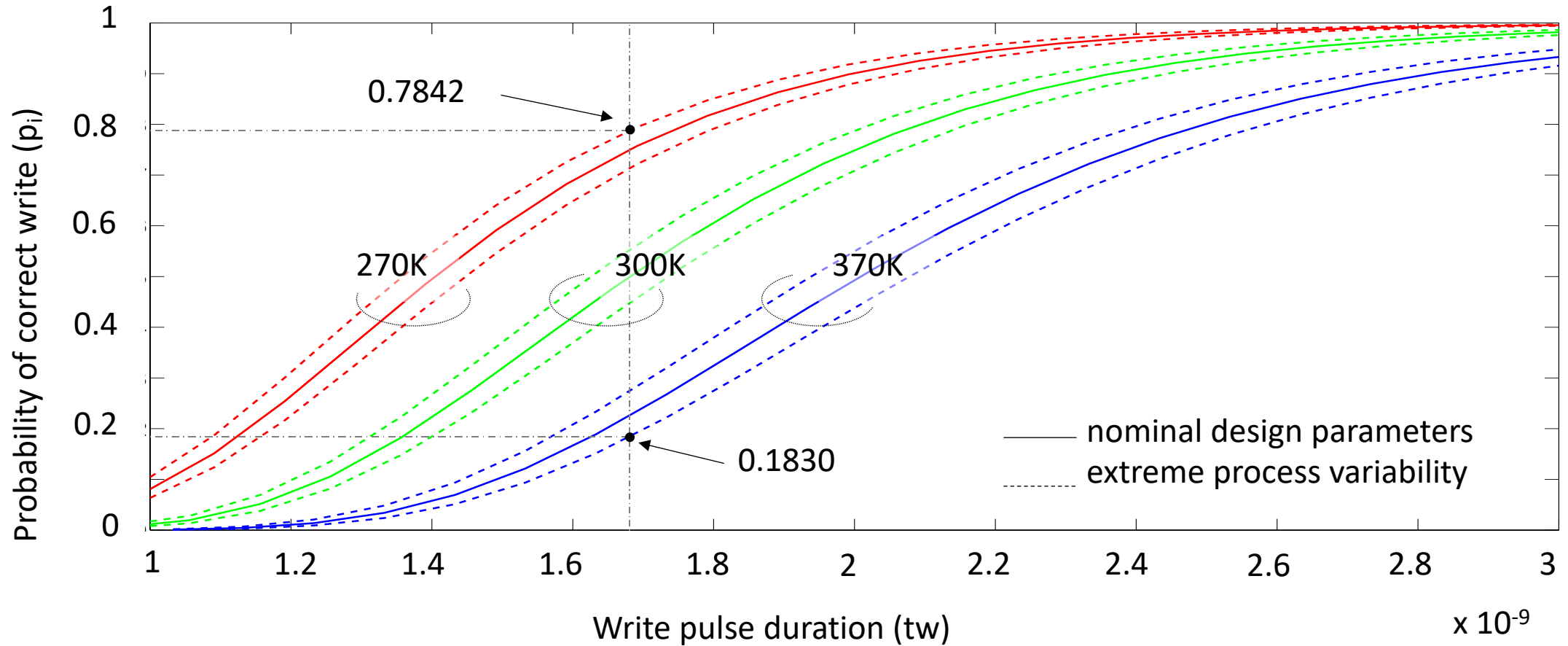
# MRAM (Magnetic Memory) - A TRNG Example -

- based on the stochasticity of MTJ write operation as source of entropy:  $H(X) = -P_{X=0} \log_2(P_{X=0}) - P_{X=1} \log_2(P_{X=1})$

*ideally  $H(1) = 1 \Rightarrow P_{X=0} = P_{X=1} = \frac{1}{2}$*

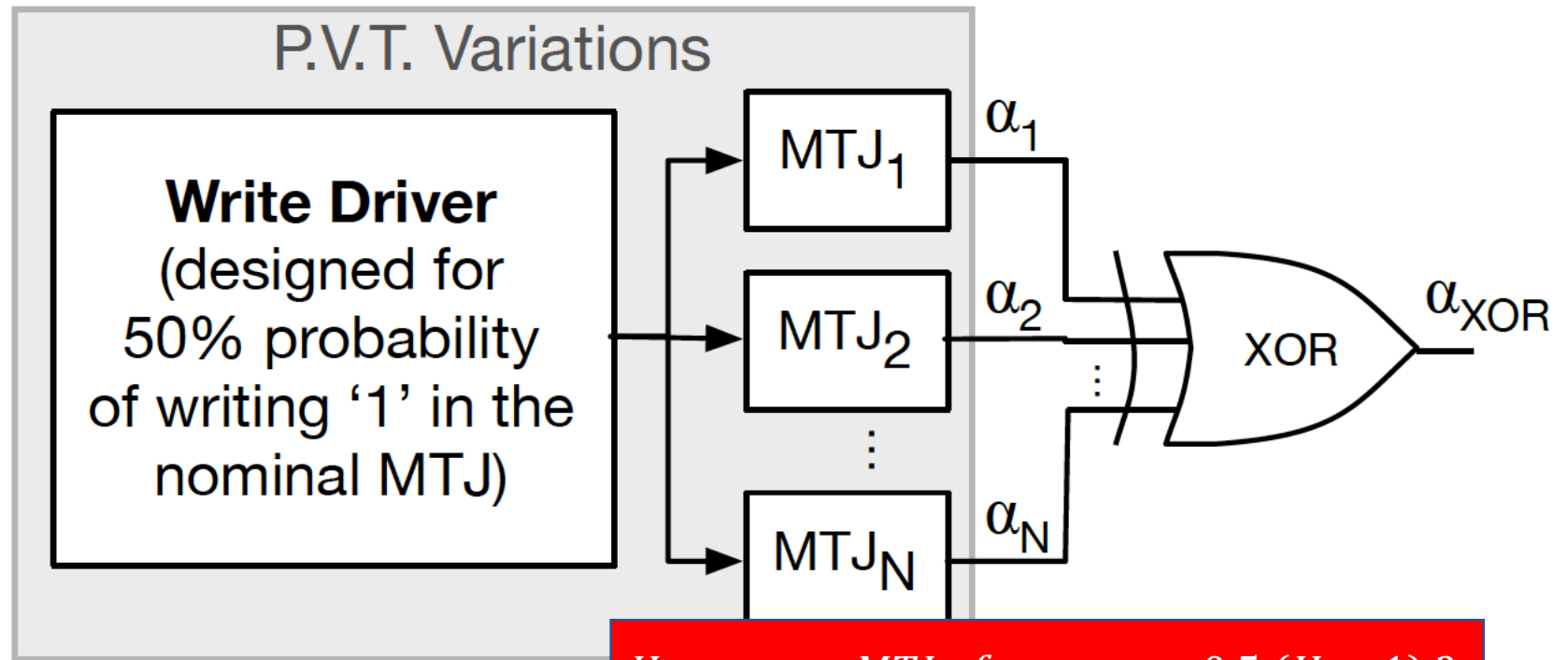


# MRAM (Magnetic Memory) - A TRNG Example -





# MRAM (Magnetic Memory) - A TRNG Example -



*How many MTJs for  $\alpha_{XOR} = 0,5$  ( $H = 1$ ) ?*

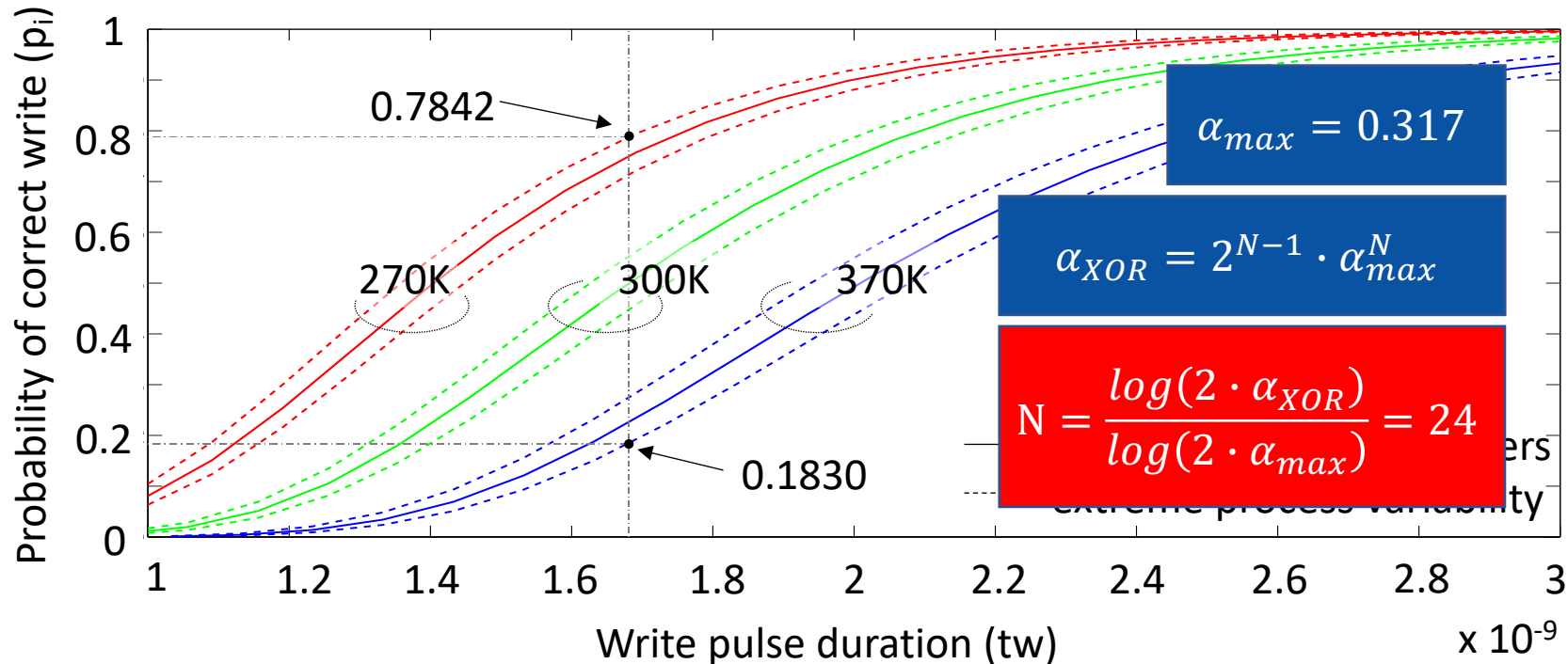
with  $\alpha_i = \left| \frac{1}{2} - P_i^{MTJ} \right|$

$$P_{XOR} = P_1^{MTJ} \cdot (1 - P_2^{MTJ}) + P_2^{MTJ} \cdot (1 - P_1^{MTJ})$$

$$\Rightarrow \alpha_{XOR} = 2^{N-1} \cdot \alpha_1 \cdots \alpha_N$$

# MRAM (Magnetic Memory) - A TRNG Example -

- Question: how many MTJs for high entropy?

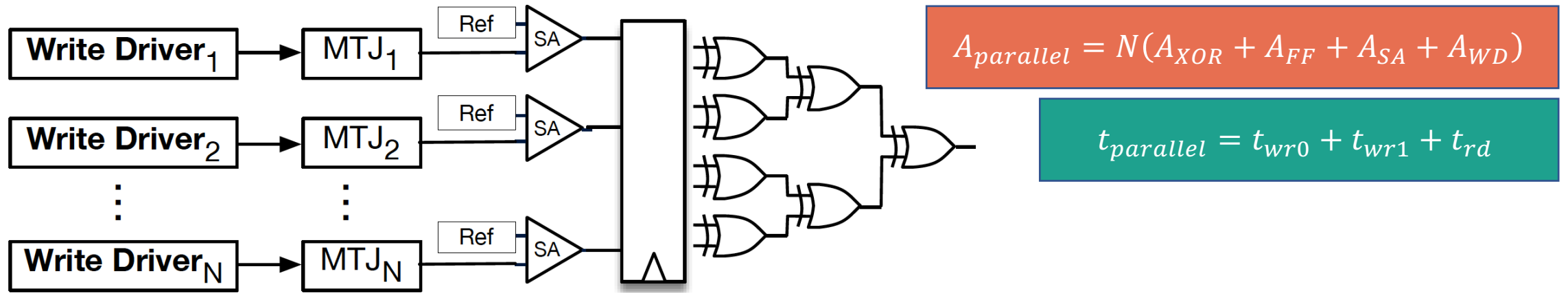


# MRAM (Magnetic Memory) - A TRNG Example -

NIST test results assuming various values of  $\alpha_{XOR}$

$\alpha$	Frequency	BlockFrequency	CumulativeSums	Runs	LongestRun	Rank	FFT	NonOverlapTemplate	Universal	ApproxEntropy	RandomExcursions	RandomExcVariant	Serial	LinearComplexity
$10^{-2}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$10^{-3}$	0	188	0	0	889	1009	1014	0	992	0	0	0	770	1014
$10^{-4}$	724	1011	726	991	1011	1011	1023	1024	1011	1006	387	388	1013	1015
$10^{-5}$	1010	1014	1012	1015	1010	1010	1011	1024	1011	1008	641	636	1015	1012
$10^{-6}$	1018	1019	1015	1013	1012	1013	1012	1024	1016	1011	655	655	1017	1016
$10^{-7}$	1014	1015	1017	1012	1011	1014	1012	1024	1015	1009	633	631	1011	1009
<b>Threshold</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>1004</b>	<b>610</b>	<b>610</b>	<b>1004</b>	<b>1004</b>
$10^{-2}$	0	0	0	0	0	0	0	0	0	0	0	0	0	1
$10^{-3}$	0	0	0	0	0	1	1	0	0	0	0	0	0	1
$10^{-4}$	0	1	0	0	1	1	1	1	1	1	0	0	1	1
$10^{-5}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$10^{-6}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$10^{-7}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1

# MRAM (Magnetic Memory) - A TRNG Example -

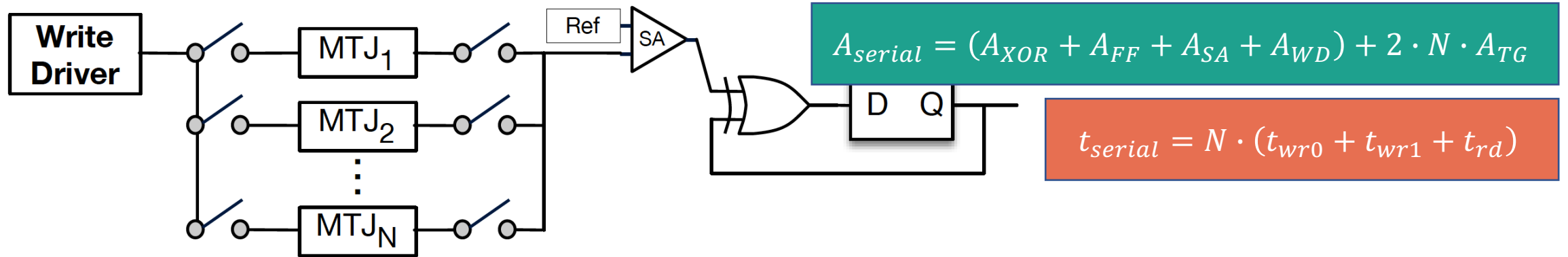


$$A_{parallel} = N(A_{XOR} + A_{FF} + A_{SA} + A_{WD})$$

$$t_{parallel} = t_{wr0} + t_{wr1} + t_{rd}$$

(a) Parallel Implementation

(b) Serial Implementation



$$A_{serial} = (A_{XOR} + A_{FF} + A_{SA} + A_{WD}) + 2 \cdot N \cdot A_{TG}$$

$$t_{serial} = N \cdot (t_{wr0} + t_{wr1} + t_{rd})$$

- 
- Many devices - very varied physics - all with intrinsic stochasticity
  - Challenging evaluation for new devices
  - Many frameworks developing in parallel
  - Material/Device engineering today mitigates stochasticity
  
  - Device/Technology co-optimization (DTCO) needed!

---

# Generating Random Numbers with Spintronic and Memristive Devices

Elena Ioana Vătăjelu

CR CNRS