Magnetic tunnel junction beyond memory – from logic to neuromorphic computing

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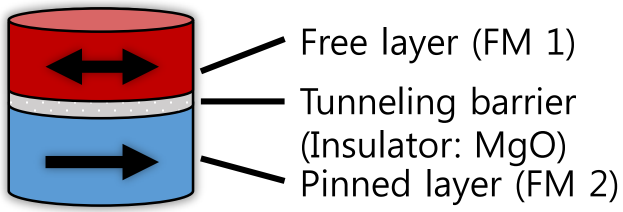
Magnetic Tunnel Junctions (MTJs)

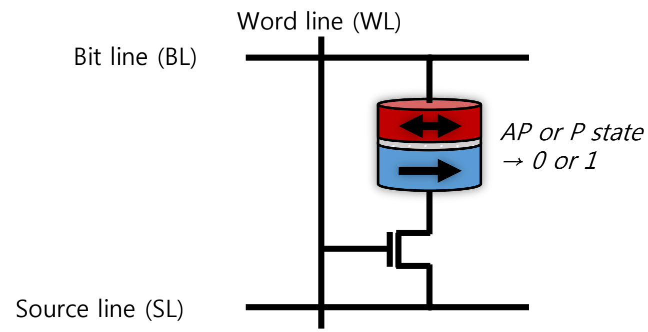
- **Structure**



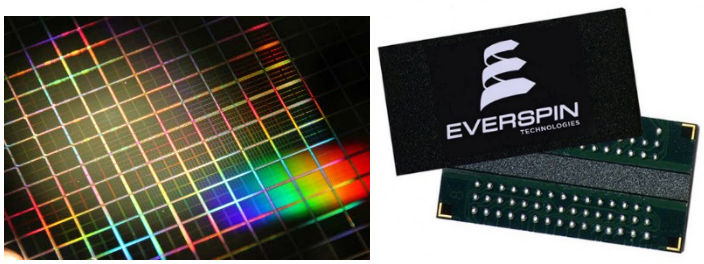
- **Function**
  - ✓ Representation of non-volatile binary state according to magnetization configuration

- **Advantage**
  - ✓ Scalability
  - ✓ Low energy
  - ✓ High speed
  - ✓ High endurance
  - ✓ CMOS compatibility

- **High density memory**



1 Transistor + 1 MTJ



1GB STT-MRAM, Everspin (2016)

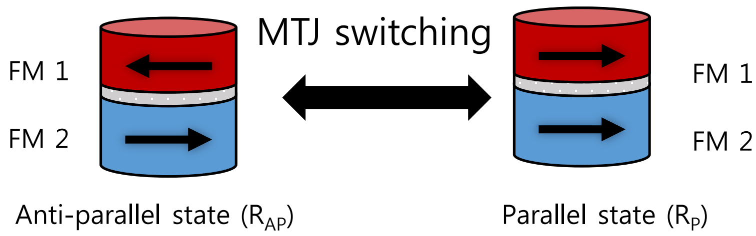
Content

" To find computing functions beyond memory from MTJ for integrated circuits"

- **Construction of 2-input MTJ**
- **MTJ Logic gates**
- **Neuromorphic computing**
  - Artificial MTJ neuron
  - Artificial MTJ synapse
  - Artificial Neurotransmission system

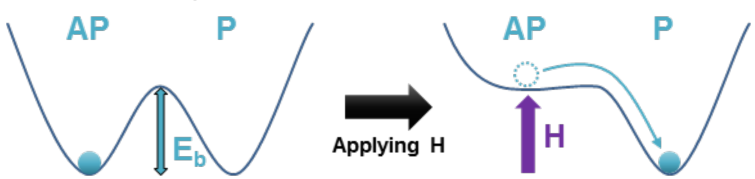
Basic configuration of MTJ

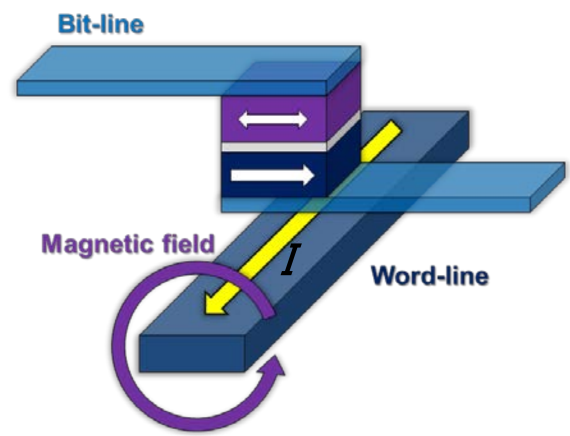
- **Single input configuration for switching to achieve the binary state**



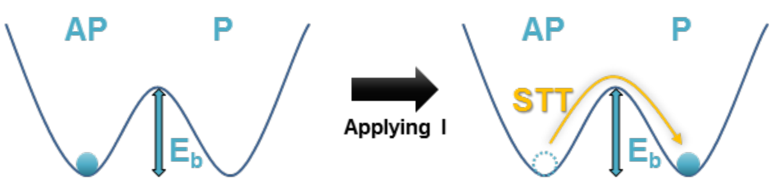
✓ Methods for magnetization reversal of free layer

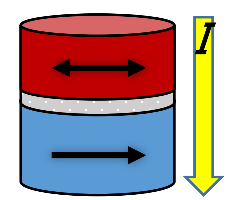
- Switching variable 1: magnetic field switching (current induced Ampere field)





- Switching variable 2: Spin-transfer torque (STT) switching (spin polarized current)





Two-input configuration of MTJ

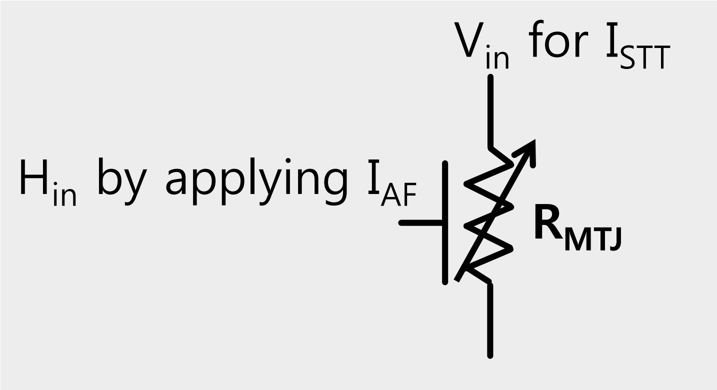
- **Motivation for multiple input extension**

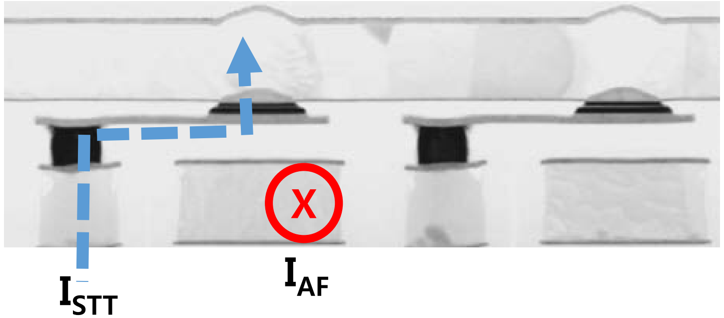
  " Increase of functional flexibility"

  - Reduction of switching stress by breakup of biases
  - Increase of switching bias margin

- **Physical variables for MTJ switching**

  - Ampere field-induce switching
  - Spin-transfer torque (STT) switching
  - Thermally assisted switching (TAS)
  - Voltage-assisted switching (ME effect)
  - Spin-orbit torque (SOT) switching





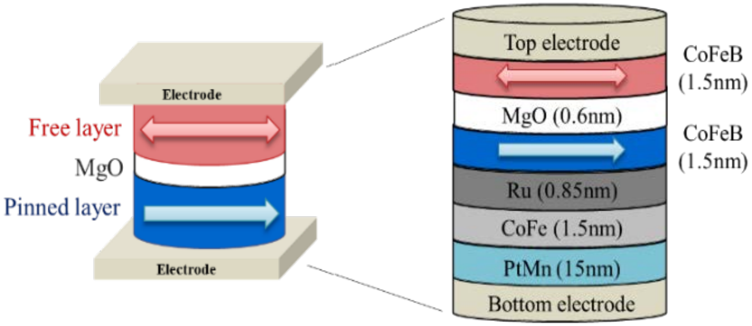
Structure of 2-input MTJ

Multiple input is available for MTJ

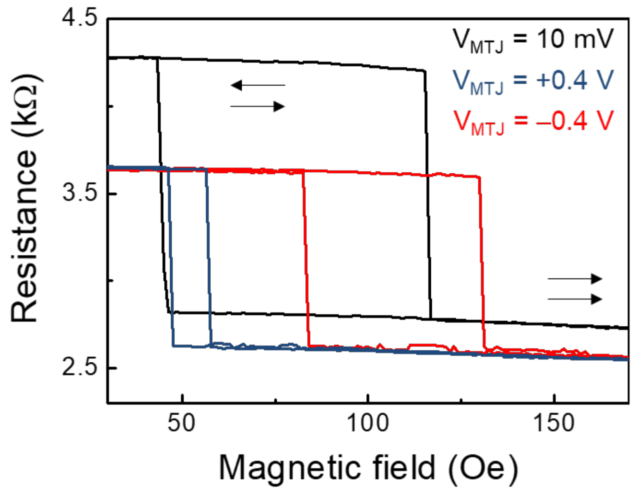
→ Our choice: STT & Ampere field for two switching inputs
→ Sharing integration methods developed for MRAM

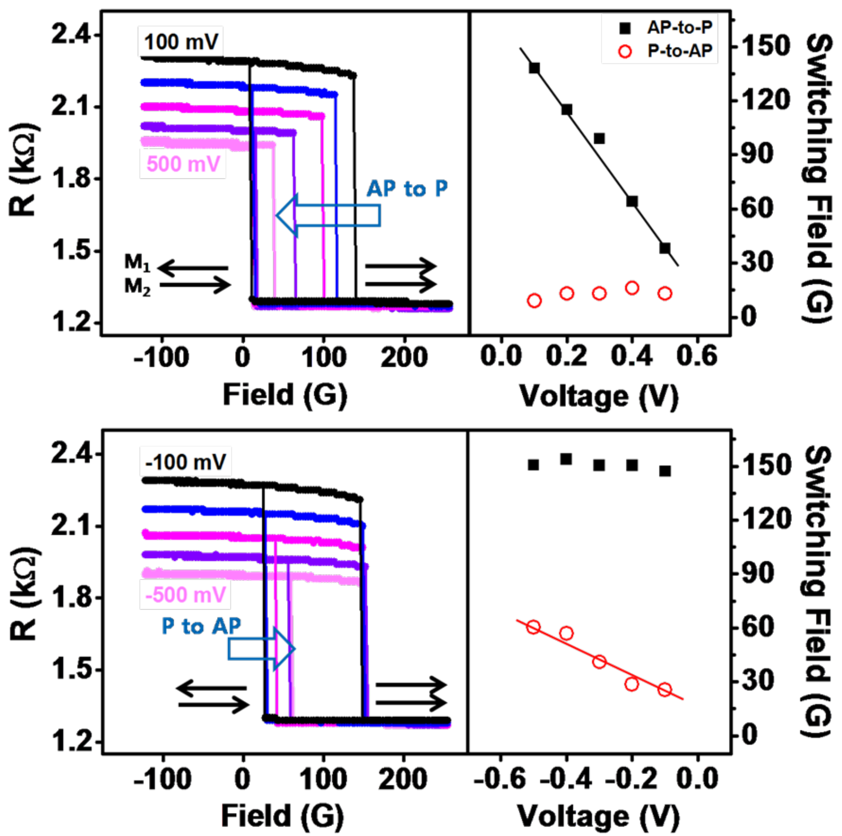
Switching characteristics of 2-input MTJ

- **MTJs for switching characteristics due to mixed inputs of STT & Ampere field**

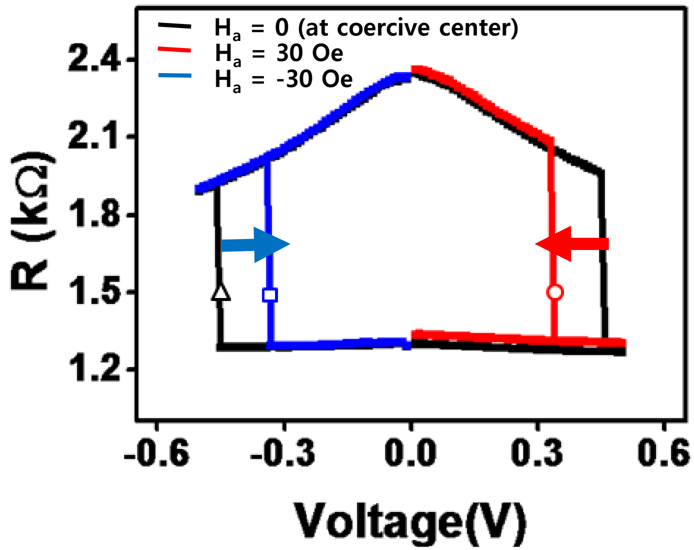


Size : (80 × 80) ~ (150 × 600) nm^2

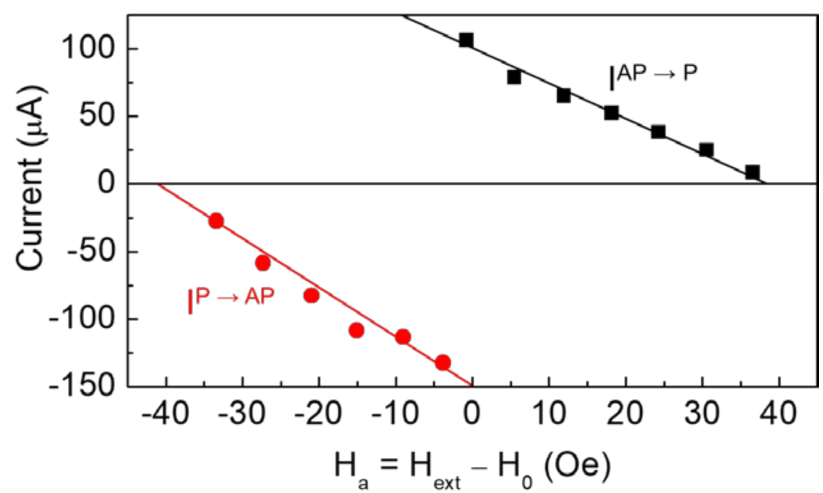




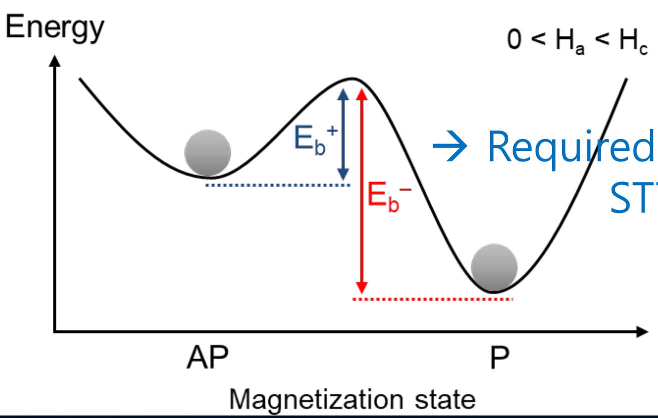
Interpretation of 2-input switching



"Magnetic field assisted STT switching"



- **Case for switching to be P state**



→ Required energy for STT switching

$E_b^+ = E_{b0} - E_b^*$

Energy due to Ampere field ($H_{ext} = H_a$) :

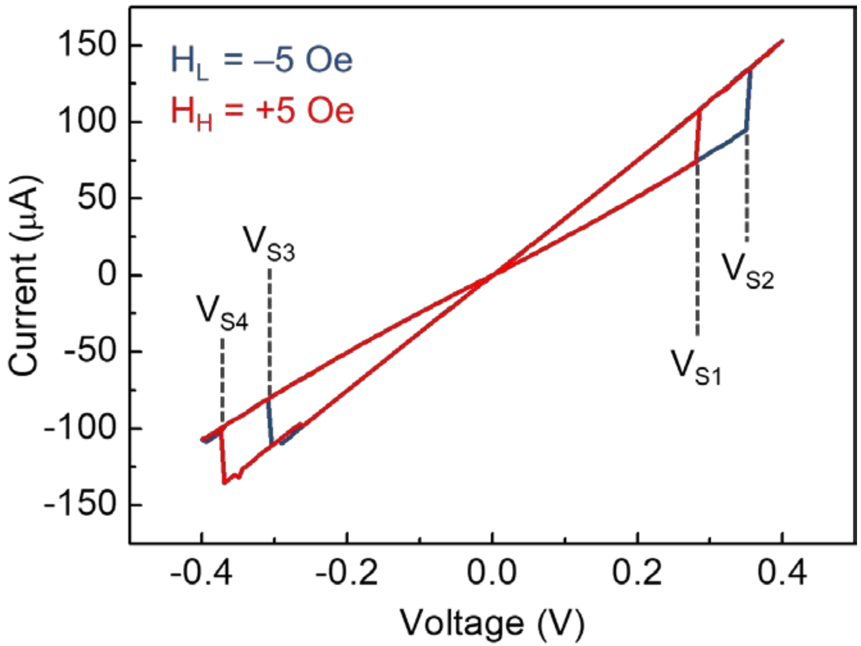
$$E_b^* = E_b(H_{ext})\left(1 - \frac{a_J}{a_c}\right) = E_0\left(1 - \frac{H_{ext}}{H_s}\right)^{\beta}\left(1 - \frac{a_J}{a_c}\right)$$

- H_s : Switching field
- E_0 : Energy barrier at zero magnetic field
- a_J : Spin transfer torque
- a_c : Critical spin transfer torque
- $\beta = 2$

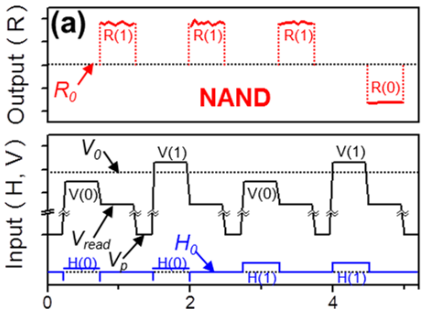
NAND/NOR representation

- **Definition of binary states for each input**

Logic value	Input 1 (V)	Input 2 (H)	MTJ OUT
1	V_H	H_H	R_{AP}
0	V_L	H_L	R_P

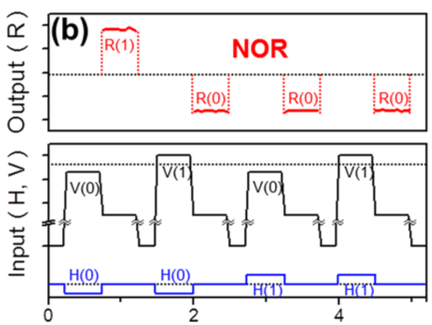


- **Assignment of input values to the STT input terminal**



V	H	R
0	0	0
1	0	0
0	1	0
1	1	1

V_L =0.2 V(<V_{S1}), V_H=0.3 V (V_{S1}<V_H<V_{S2})
H_L =-5 (Oe), H_H= 5 (Oe)



V	H	R
0	0	1
1	0	0
0	1	0
1	1	0

V_L =0.3 V (V_{S1}<V_L<V_{S2}), V_H=0.4 V (>V_{S2})
H_L =-5 (Oe), H_H= 5 (Oe)

All logical representation founded in MTJ

- **7 Boolean logic representations from possible 12 binary inputs of voltage biases for the STT switching**

No.	Initial State	Input set				Input (V, H), Output (R)				Logic function	
		V_L	V_H	H_L	H_H	(V_L,H_L)	(V_H,H_L)	(V_L,H_H)	(V_H,H_H)	R_{AP} = 1, R_P = 0	R_{AP} = 0, R_P = 1
1	R_{AP}	0.2	0.3	–5 Oe	5 Oe	R_{AP}	R_{AP}	R_{AP}	R_P	**NAND**	**AND**
2		0.3	0.4			R_{AP}	R_P	R_P	R_P	**NOR**	**OR**
3		0.2	0.4			R_{AP}	R_P	R_{AP}	R_P	**NOT V**	**V**
4		0.2	0.2			R_{AP}	R_{AP}	R_{AP}	R_{AP}	**TRUE**	**FALSE**
5		0.3	0.3			R_{AP}	R_{AP}	R_P	R_P	**NOT H**	**H**
6		0.3	0.3			R_P	R_P	R_P	R_P	FALSE	TRUE
7	R_P	–0.25	–0.35			R_P	R_{AP}	R_P	R_P	**V NIMP H**	**V IMP H**
8		–0.35	–0.45			R_{AP}	R_{AP}	R_P	R_{AP}	**H IMP V**	**H NIMP V**
9		–0.25	–0.45			R_P	R_{AP}	R_P	R_{AP}	V NIMP H	V IMP H
10		–0.25	–0.25			R_P	R_P	R_P	R_P	FALSE	TRUE
11		–0.35	–0.35			R_{AP}	R_{AP}	R_P	R_P	NOT H	H
12		–0.45	–0.45			R_{AP}	R_{AP}	R_{AP}	R_{AP}	TRUE	FALSE

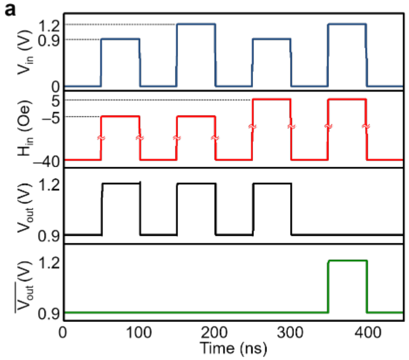
MTJ Logic gate

- **Logic gate for digital computing**

  - Cascading computing

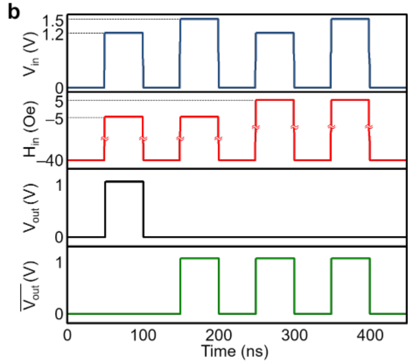
Full schematic of a logic gate

14 Boolean functions computed in MTJ logic gate



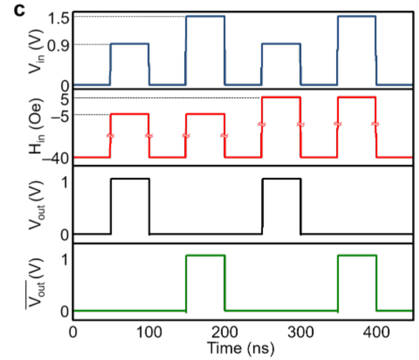
V	H	NAND
0	0	1
1	0	1
0	1	1
1	1	0

V	H	OR
0	0	0
1	0	0
0	1	0
1	1	1



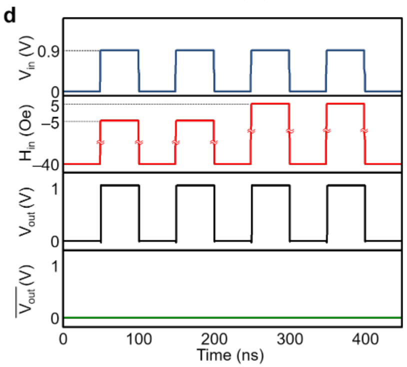
V	H	NOR
0	0	1
1	0	0
0	1	0
1	1	0

V	H	OR
0	0	0
1	0	1
0	1	1
1	1	1



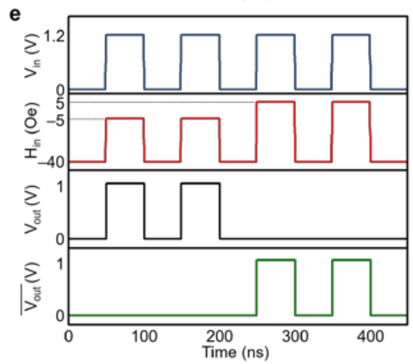
V	H	NOT V
0	0	1
1	0	0
0	1	1
1	1	0

V	H	V
0	0	0
1	0	1
0	1	0
1	1	1



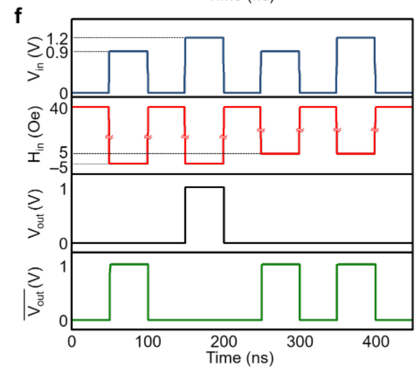
V	H	TRUE
0	0	1
1	0	1
0	1	1
1	1	1

V	H	FALSE
0	0	0
1	0	0
0	1	0
1	1	0



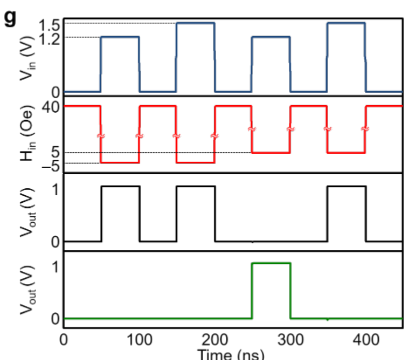
V	H	NOT H
0	0	1
1	0	1
0	1	0
1	1	0

V	H	H
0	0	0
1	0	0
0	1	1
1	1	1



V	H	V NIMP H
0	0	0
1	0	1
0	1	0
1	1	0

V	H	V IMP H
0	0	1
1	0	0
0	1	1
1	1	1



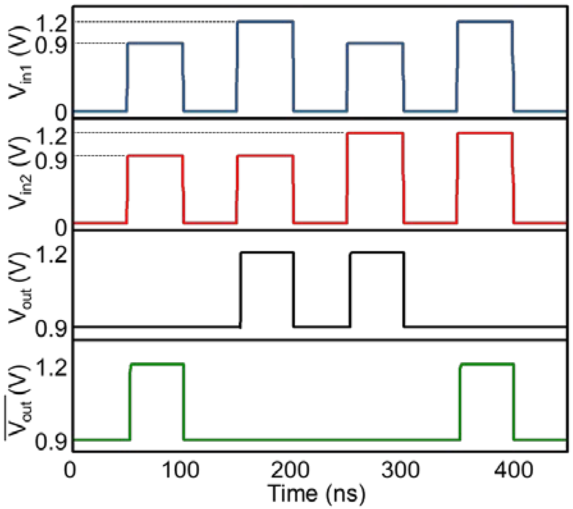
V	H	H IMP V
0	0	1
1	0	1
0	1	0
1	1	1

V	H	H NIMP V
0	0	0
1	0	0
0	1	1
1	1	0

- **Each function is confirmed by SPICE simulation modified with MTJ micro-model**
- **XOR and XNOR are missing among full 16 Boolean logics**

XOR/XNOR MTJ Logic gate

- XOR/XNOR gate could be completed by using “cascading computing”



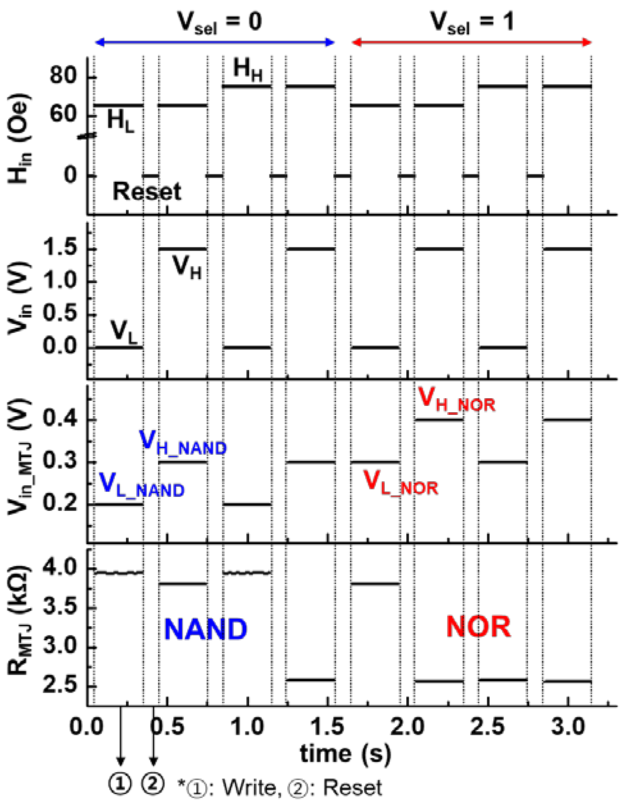
V	H	XOR
0	0	0
1	0	1
0	1	1
1	1	0

V	H	XNOR
0	0	1
1	0	0
0	1	0
1	1	1

- **Conclusively, we have two types of MTJ logic gate which allow any digital computing**

Reconfigurable Logic

- **Reconfigurability: further advantage of MTJ logic**

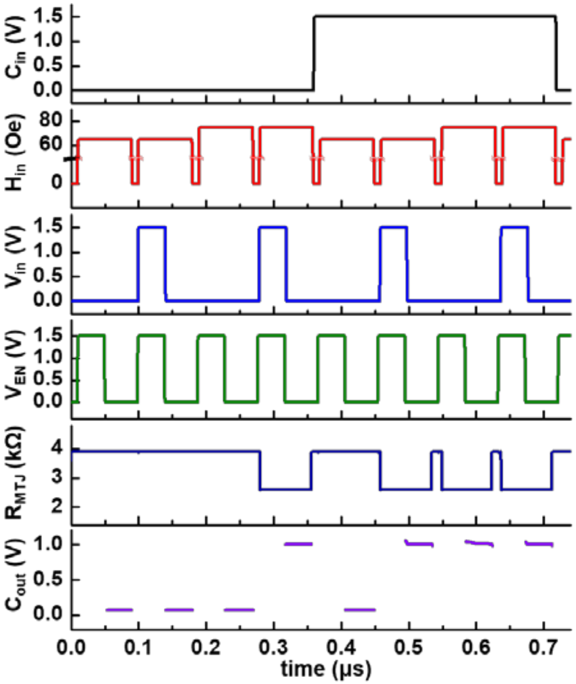


H_{in}	V_{in}	V_{sel}	V_{in_MTJ}	R_{MTJ}	
0	0	0	V_{L_NAND}	1	"NAND" @ V_{sel} = 0
0	1	0	V_{H_NAND}	1	
1	0	0	V_{L_NAND}	1	
1	1	0	V_{H_NAND}	0	
0	0	1	V_{L_NOR}	1	"NOR" @ V_{sel} = 1
0	1	1	V_{H_NOR}	0	
1	0	1	V_{L_NOR}	0	
1	1	1	V_{H_NOR}	0	

< Truth table >

Practical example for reconfigurable Logic

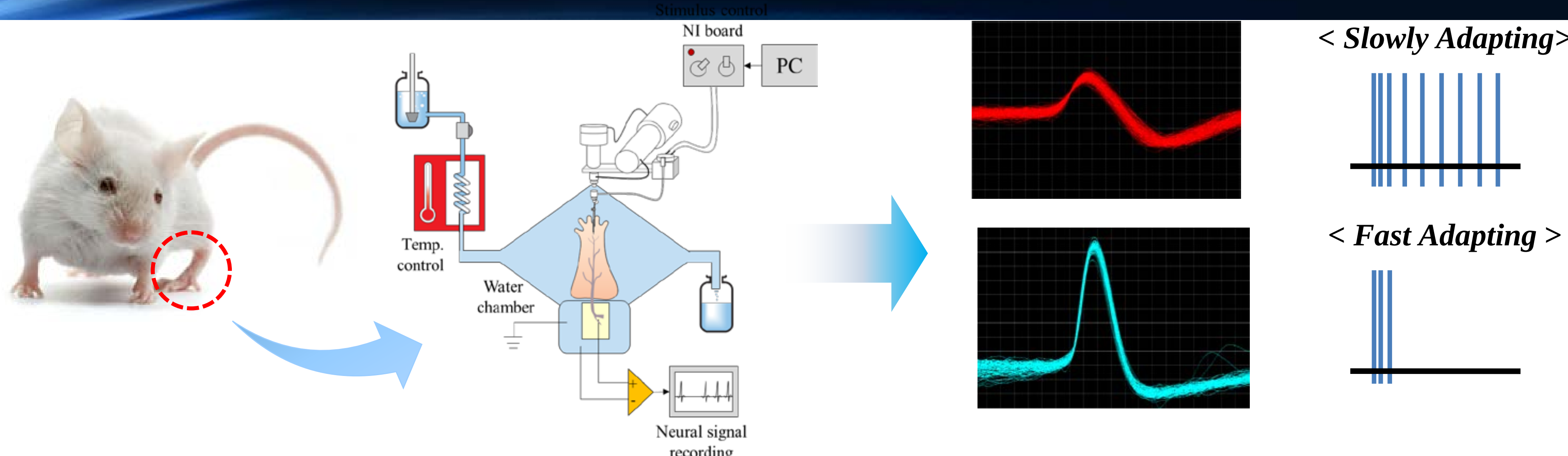
- **Carry-out function with reconfigurable logic**

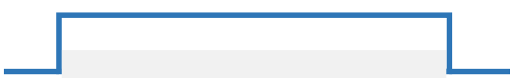
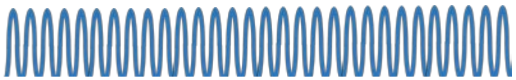
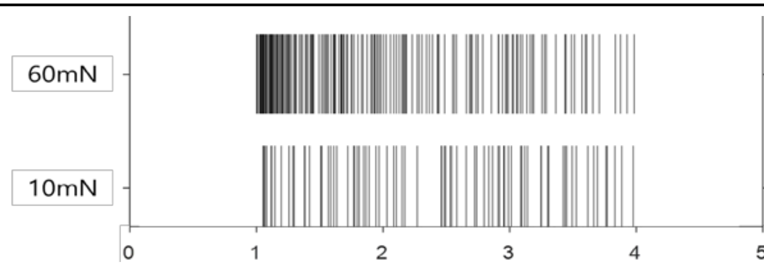
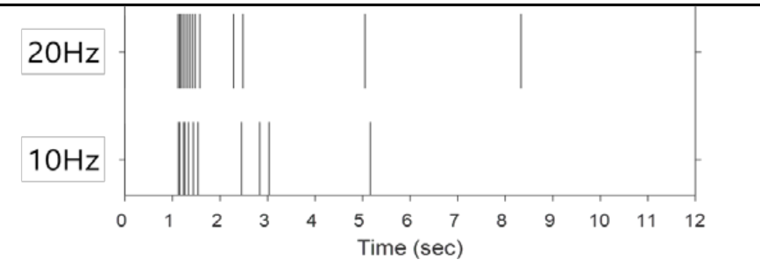
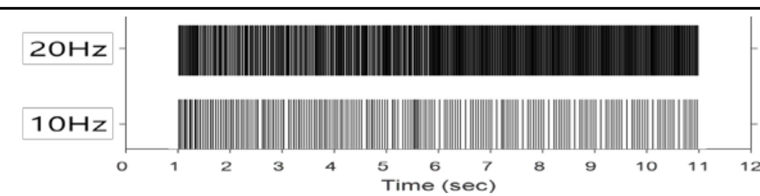


Input			Output	
H_{in}	V_{in}	C_{in}	C_{out}	
0	0	0	0	"AND" @ C_{in}=0
0	1	0	0	
1	0	0	0	
1	1	0	1	
0	0	1	0	"OR" @ C_{in}=1
0	1	1	1	
1	0	1	1	
1	1	1	1	

< Truth table >

Neurotransmission – spike signal carrying information

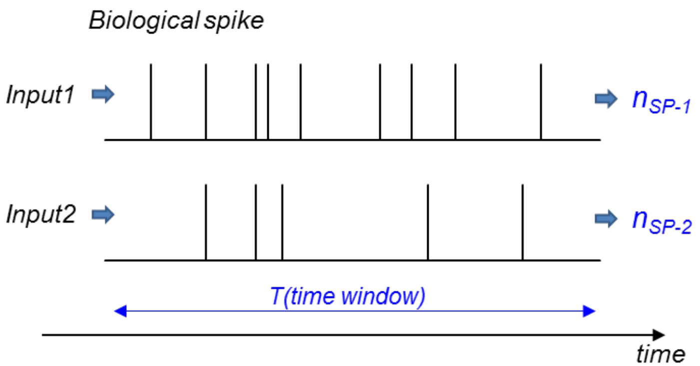


Stimulus for tactile sense	Pressure 	Frequency 
Slowly Adapting		
Fast Adapting		

Neural coding

- **Neural (Biological) coding**

  To find carrier for information according to "Strength and frequency "of input stimulus



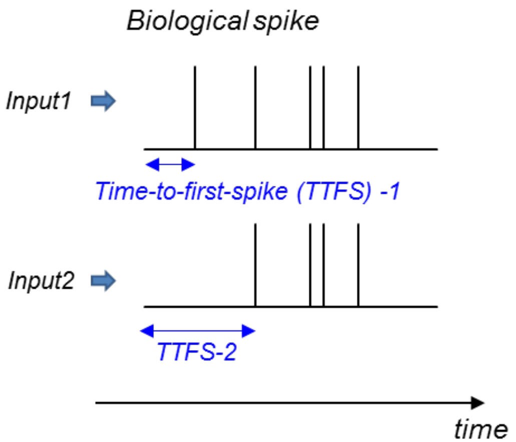
- Rate coding

✓ **Information → spiking rate**

- Temporal coding

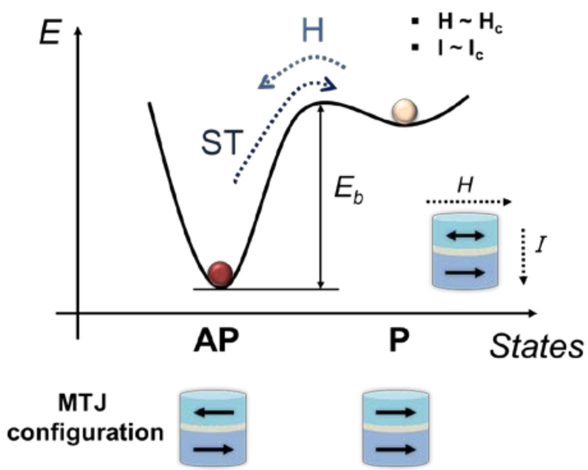
✓ **Information → Spiking pattern (Spike ordering in timing)**

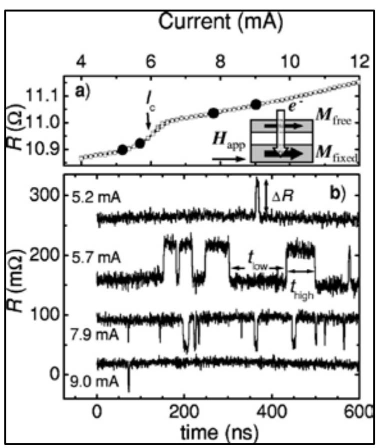
- Time-to-first-spike, Phase Correlations, Spiking sequence, Synchrony etc.



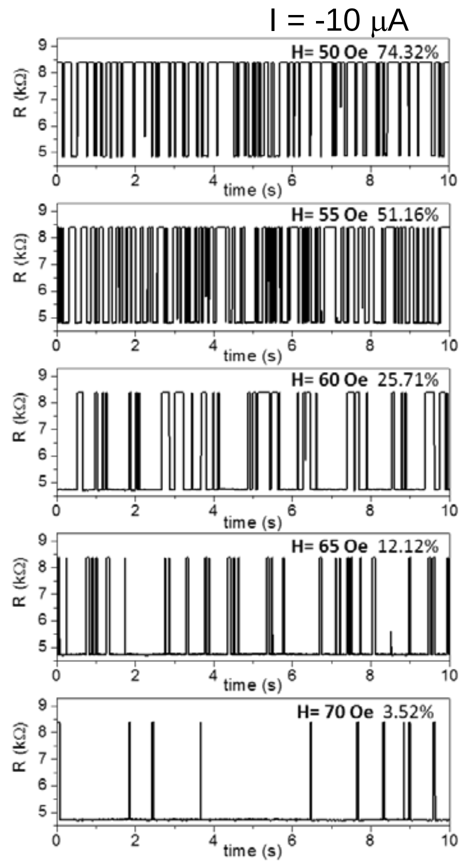
Telegraphic switching

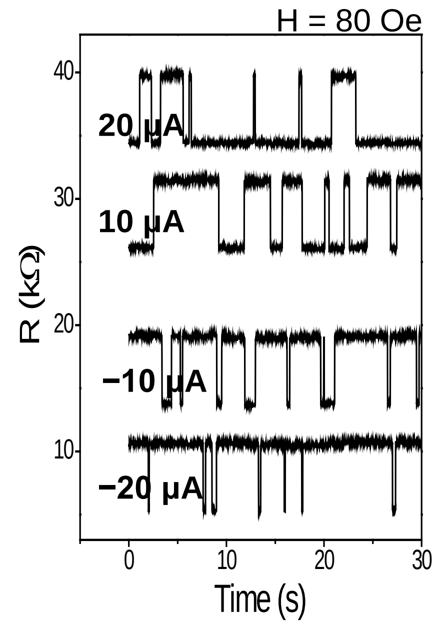
- **Telegraphic switching by mixed effect of STT & Ampere field in 2-inpt MTJ**





M. Pufall et al., Phys. Rev. B (2004)





Total Energy (E_M + E_{STT}) ~ E_S

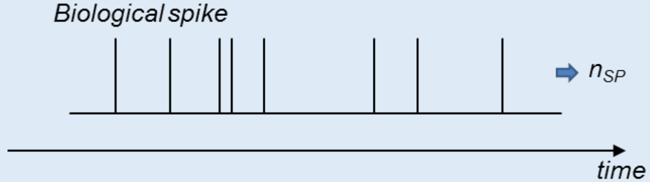
→ Toggling between AP and P state

Stochastic characteristic

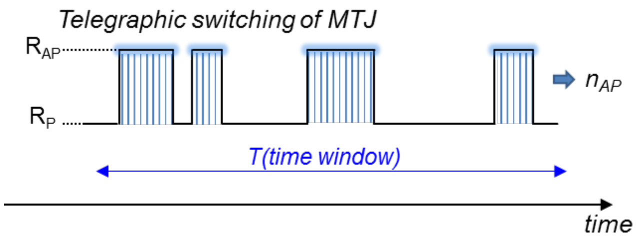
→ Switching probability P(H, I) is defined as the carried information

Rate coding

- **Construction of neural coding : Rate coding**



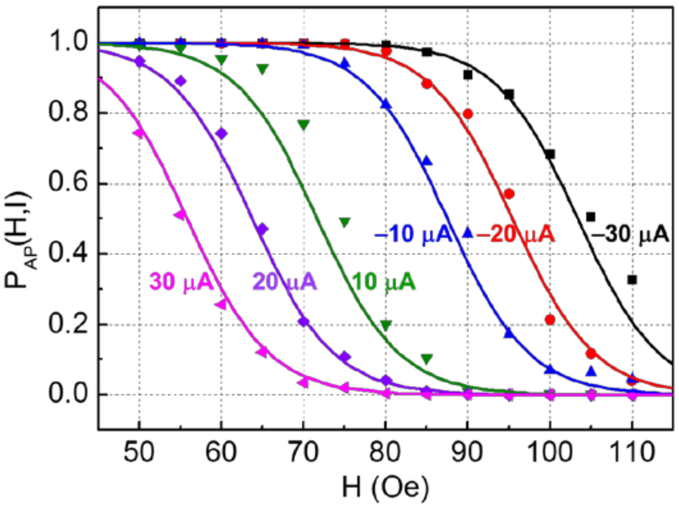
- $\boldsymbol{Rate(Biology) = \frac{n_{sp}(number\ of\ spikes)}{T\ (time\ window)}}$

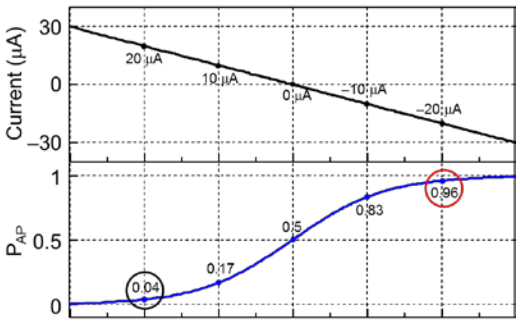


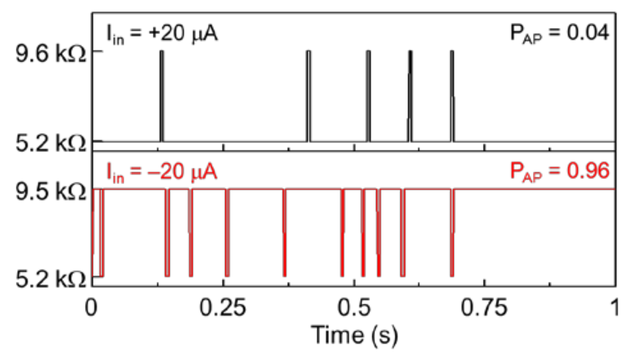
- $\boldsymbol{Rate(MTJ) = \frac{t_{AP}\ (or\ t_P)}{T\ (total\ bit)}}$ **or** $P_{AP}(H,I) = \frac{1}{1+\exp(\alpha H + \beta I + \gamma)}$

Information carrier : rate

Stimulus : H and I applied by independent inputs





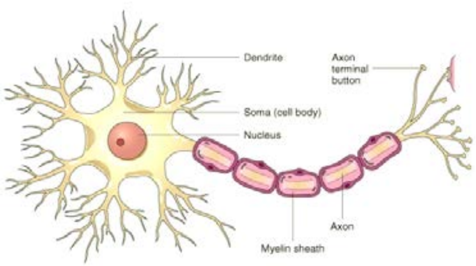


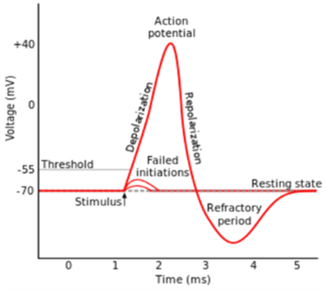
Artificial neuron function

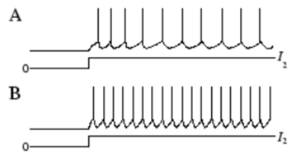
- **MTJ-based neuron architecture representing the rate coding**

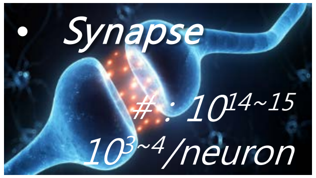
Neurotransmission

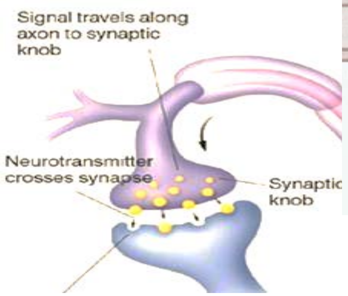
- **Neuron system connected by "Synapse"**
  (Spike-rate-dependent plasticity)

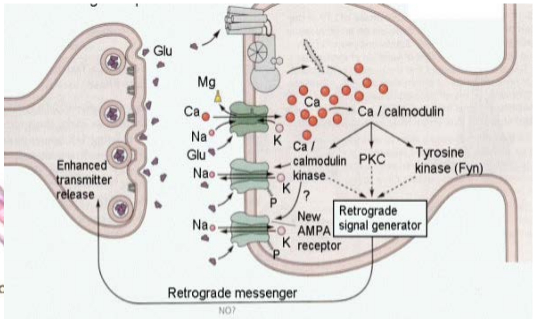












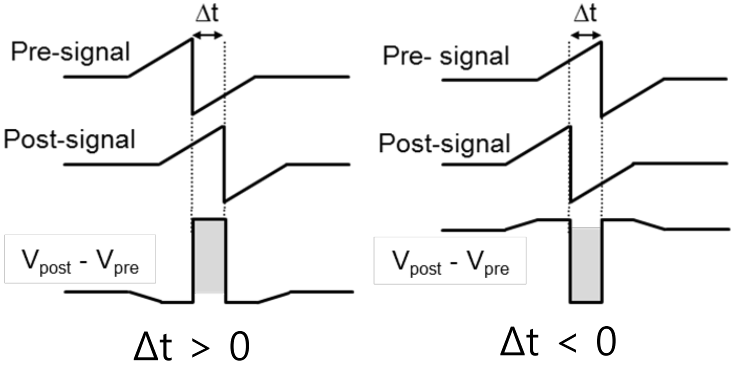
- **Spike(=Action potential) generation**
  (when the signal is above threshold)
- **Neural coding**
  - Information is coded through spike train
  - Rate coding

- **Synaptic weight: plasticity for connection strength**
- **Weight modulation**
  - Potentiation / Depression
  - Spike-timing-dependent plasticity (STDP)

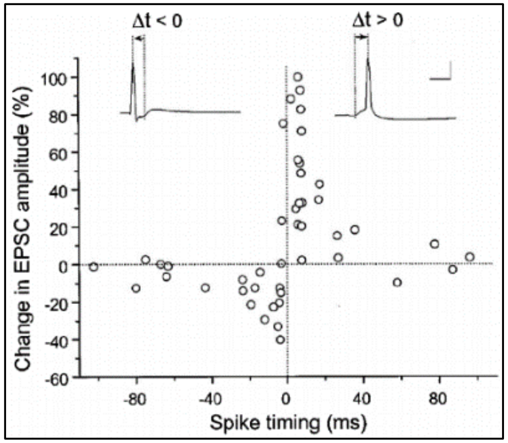
Memristive character of MTJ

MTJ-based artificial synapse

- Construction of input signal for "Spike-timing dependent plasticity"



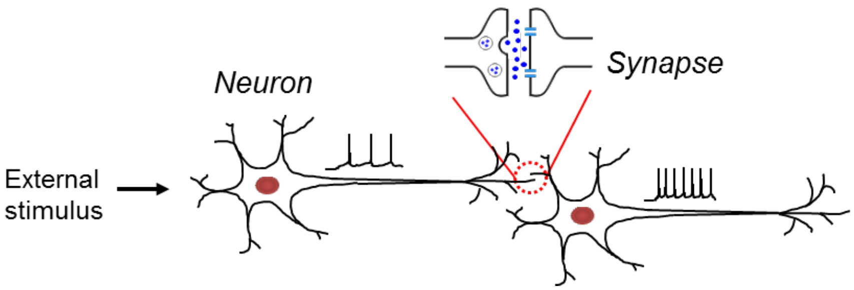
<Biological STDP>



R. Froemke et al., Nature (2002)

Artificial neurotransmission

- **Neurotransmission system**



- **Artificial neurotransmission system**

- MTJs are commonly used for neural and synaptic functions
- Learning rule of "**Spike-rate dependent plasticity**" is possibly applied

SRDP learning rule

Summary

- **MTJ was modified with two inputs for switching to achieve functional flexibility.**
- **Then we found various computing functions for digital to neuromorphic computing.**