Physics and Applications of Spin-Transfer Torques

Andrew D. Kent
Center for Quantum Phenomena
Department of Physics
New York University

NYU

CQP Center for Quantum Phenomena

Physics and Applications of Spin-Transfer Torques

Outline

- Magnetic tunnel junctions and spin-transfer torques
- Applications
- Switching of magnetization, materials and device optimization
- Cryogenic applications

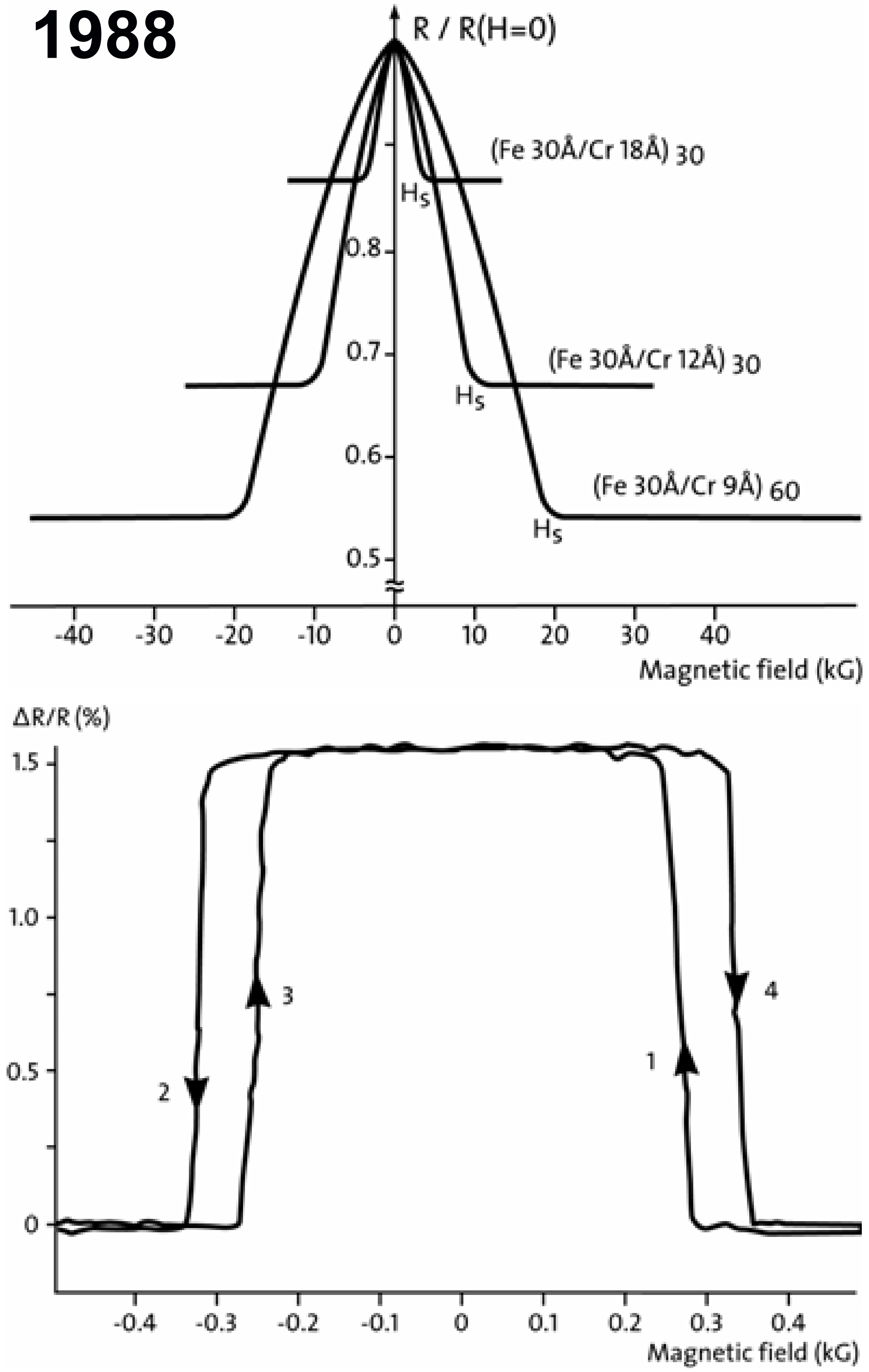
Giant Magnetoresistance (GMR)

The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Albert Fert	Peter Grünberg
1/2 of the prize	1/2 of the prize
France	Germany
Université Paris-Sud; Unité Mixte de Physique CNRS/THALES Orsay, France	Forschungszentrum Jülich Jülich, Germany
b. 1938	b. 1939

1988

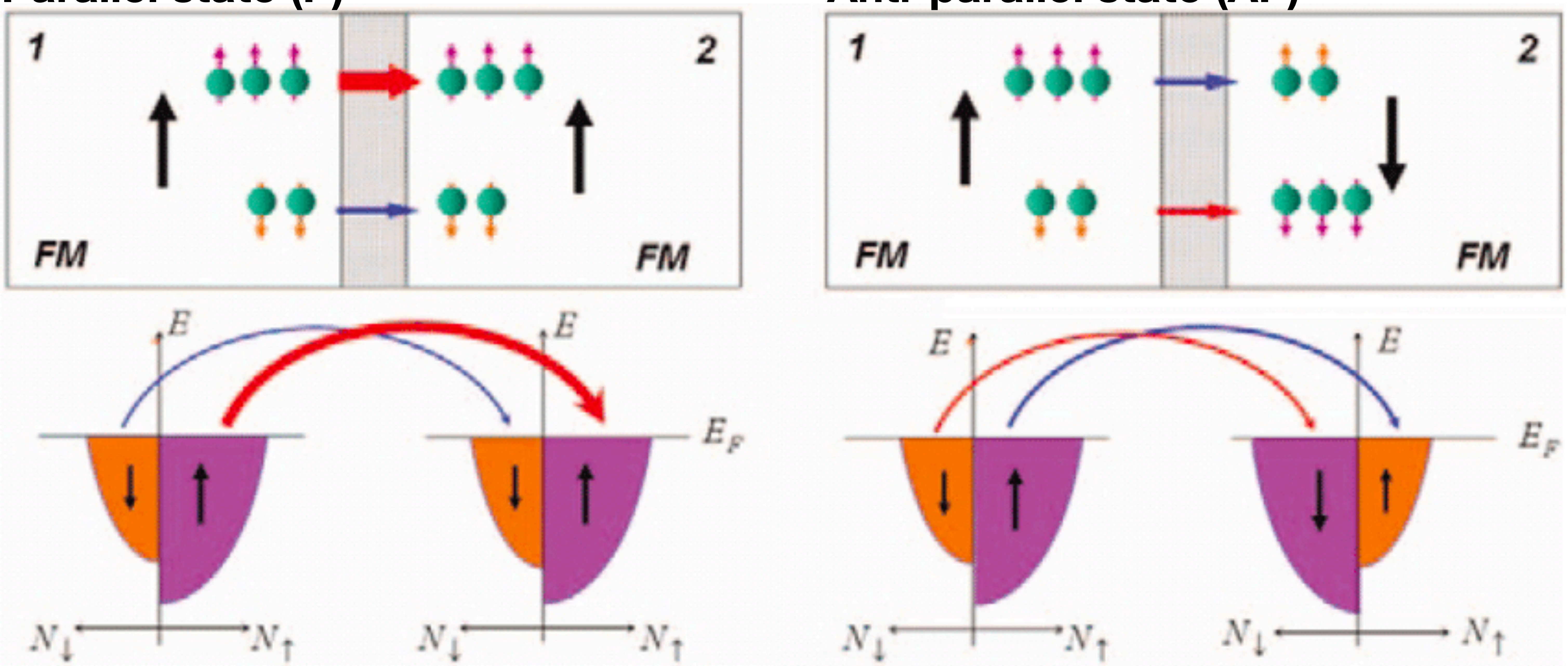


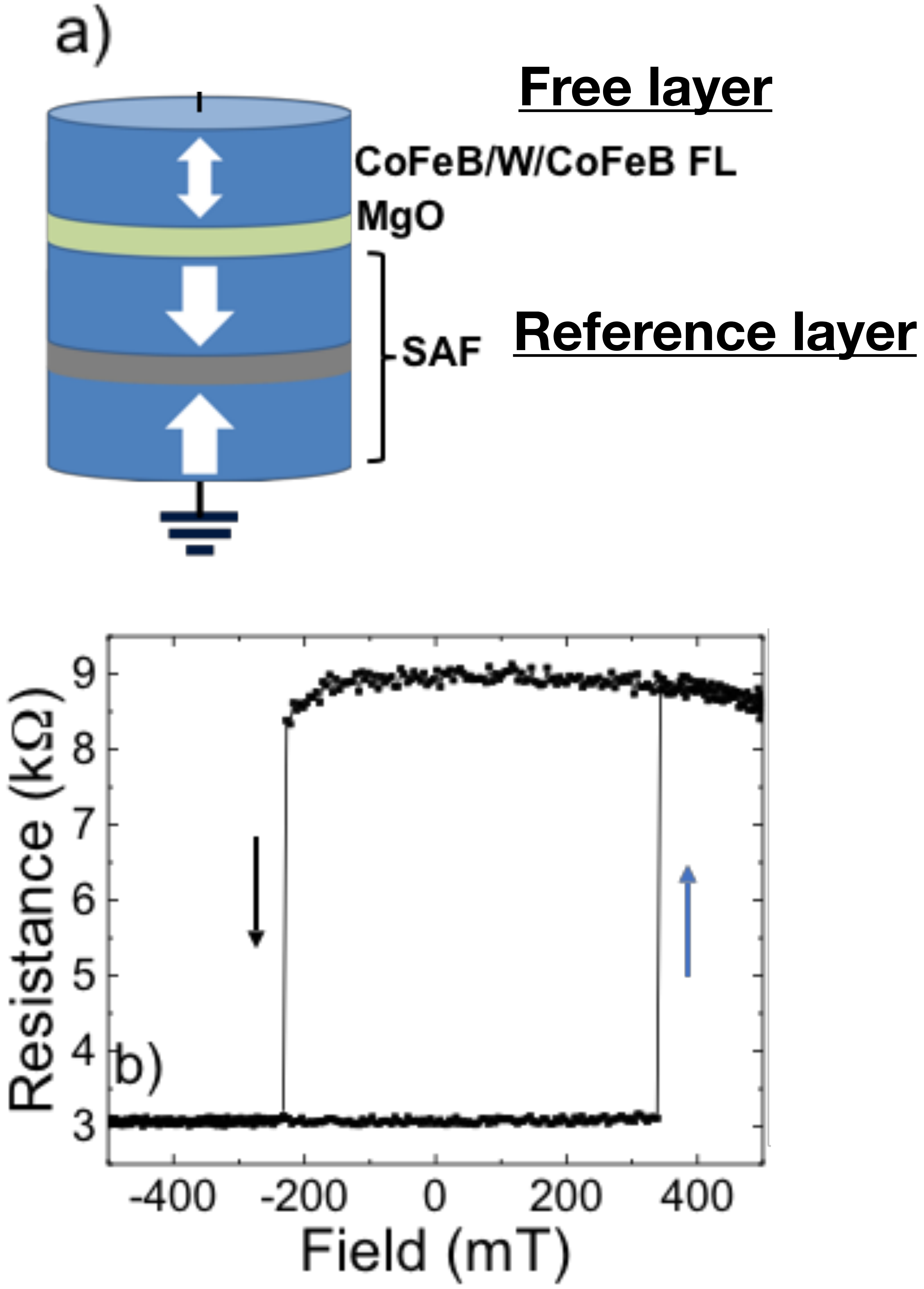
→ ‘Spintronics’= **Spin**+**Tr**ansport+Electr**onics**: control of current using the spin of electrons

Magnetic Tunnel Junction

Two ferromagnetic metals separated by an insulating barrier

Parallel state (P) **Anti-parallel state (AP)**





From:

$$P_i = \frac{N_{i\uparrow}(E_F) - N_{i\downarrow}(E_F)}{N_{i\uparrow}(E_F) + N_{i\downarrow}(E_F)}$$

Julliere's formula: $$\mathrm{TMR} = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}} = \frac{2P_1P_2}{1 - P_1P_2}$$

W. H. Butler *et al.*, Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches
PRB **63**, 054416 (2001)

NYU

Prediction of Spin-Transfer Torques

2013 Oliver E. Buckley Prize

John Slonczewski

Luc Berger

Citation:
"For predicting spin-transfer torque and opening the field of current-induced control over magnetic nanostructures."

Foundational papers:
J. C. Slonczewski, Phys. Rev. B. **39**, 6996 (1989)
J. C. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996)
L. Berger, Phys. Rev. B **54,** 9353 (1996)

NYU

Prediction of Spin-Transfer Torques

PHYSICAL REVIEW B VOLUME 39, NUMBER 10 1 APRIL 1989

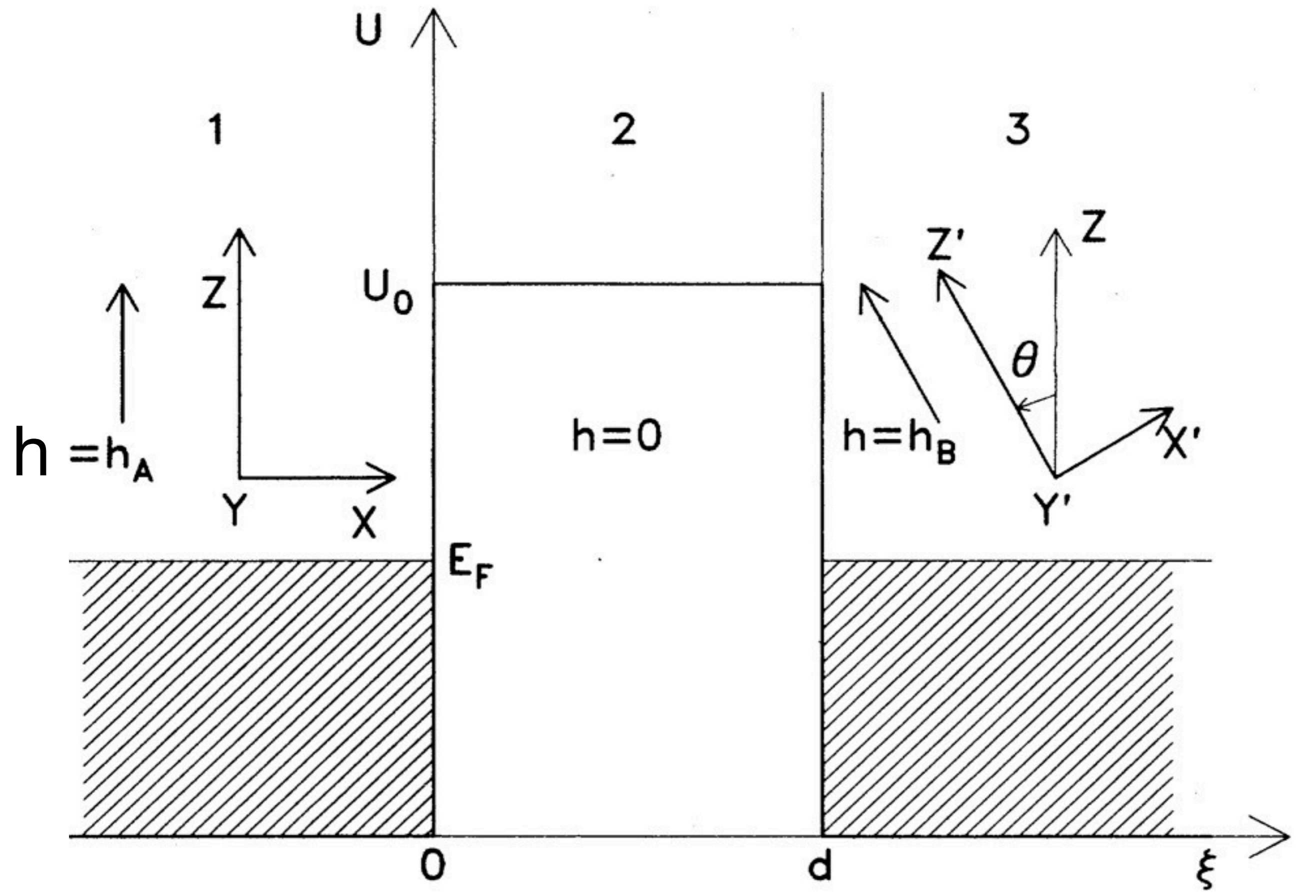
Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier

J. C. Slonczewski
IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 27 June 1988)

A theory is given for three closely related effects involving a nonmagnetic electron-tunneling barrier separating two ferromagnetic conductors. The first is Julliere's magnetic valve effect, in which the tunnel conductance depends on the angle θ between the moments of the two ferromagnets. One finds that discontinuous change of the potential at the electrode-barrier interface diminishes the spin-polarization factor governing this effect and is capable of changing its sign. The second is an effective interfacial exchange coupling $-J\cos\theta$ between the ferromagnets. One finds that the magnitude and *sign* of J depend on the height of the barrier and the Stoner splitting in the ferromagnets. The third is a new, irreversible exchange term in the coupled dynamics of the ferromagnets. For one sign of external voltage V, this term describes relaxation of the Landau-Lifshitz type. For the opposite sign of V, it describes a pumping action which can cause spontaneous growth of magnetic oscillations. All of these effects were investigated consistently by analyzing the transmission of charge and spin currents flowing through a rectangular barrier separating free-electron metals. In application to Fe-C-Fe junctions, the theory predicts that the valve effect is weak and that the coupling is antiferromagnetic ($J<0$). Relations connecting the three effects suggest experiments involving small spatial dimensions.

$$\mathrm{TMR} = \frac{2P_1P_2}{1-P_1P_2}$$

In magnetic tunnel junctions



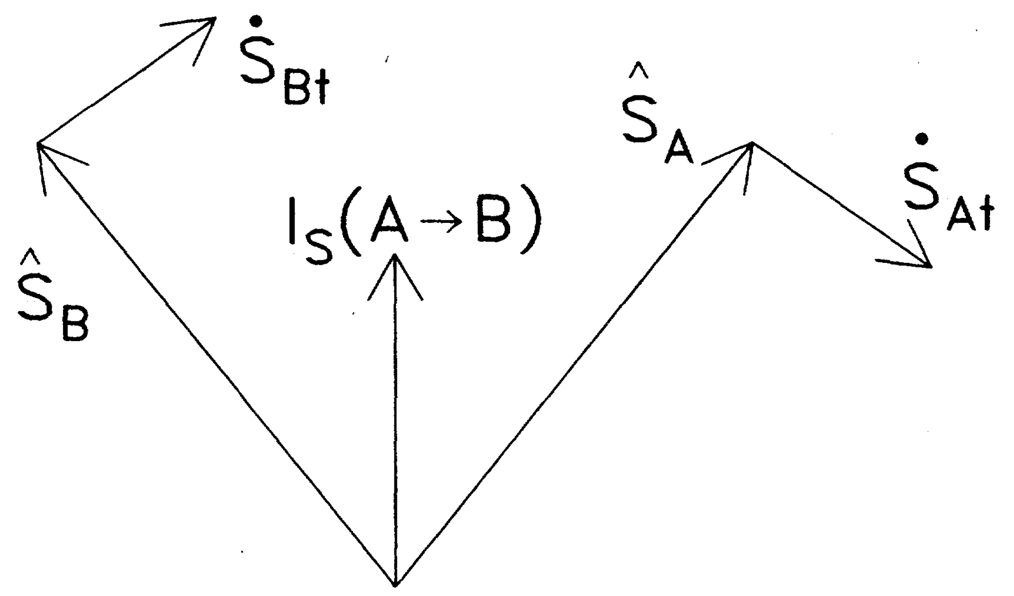


FIG. 6. Scheme of spin-vector dynamics due to the transverse terms of dissipative exchange coupling induced by an external voltage across the barrier.

In magnetic metallic multilayers

J. C. Sloncewski, JMMM **159**, L1-L7 (1996)
L. Berger, PRB **54**, 9353 (1996)

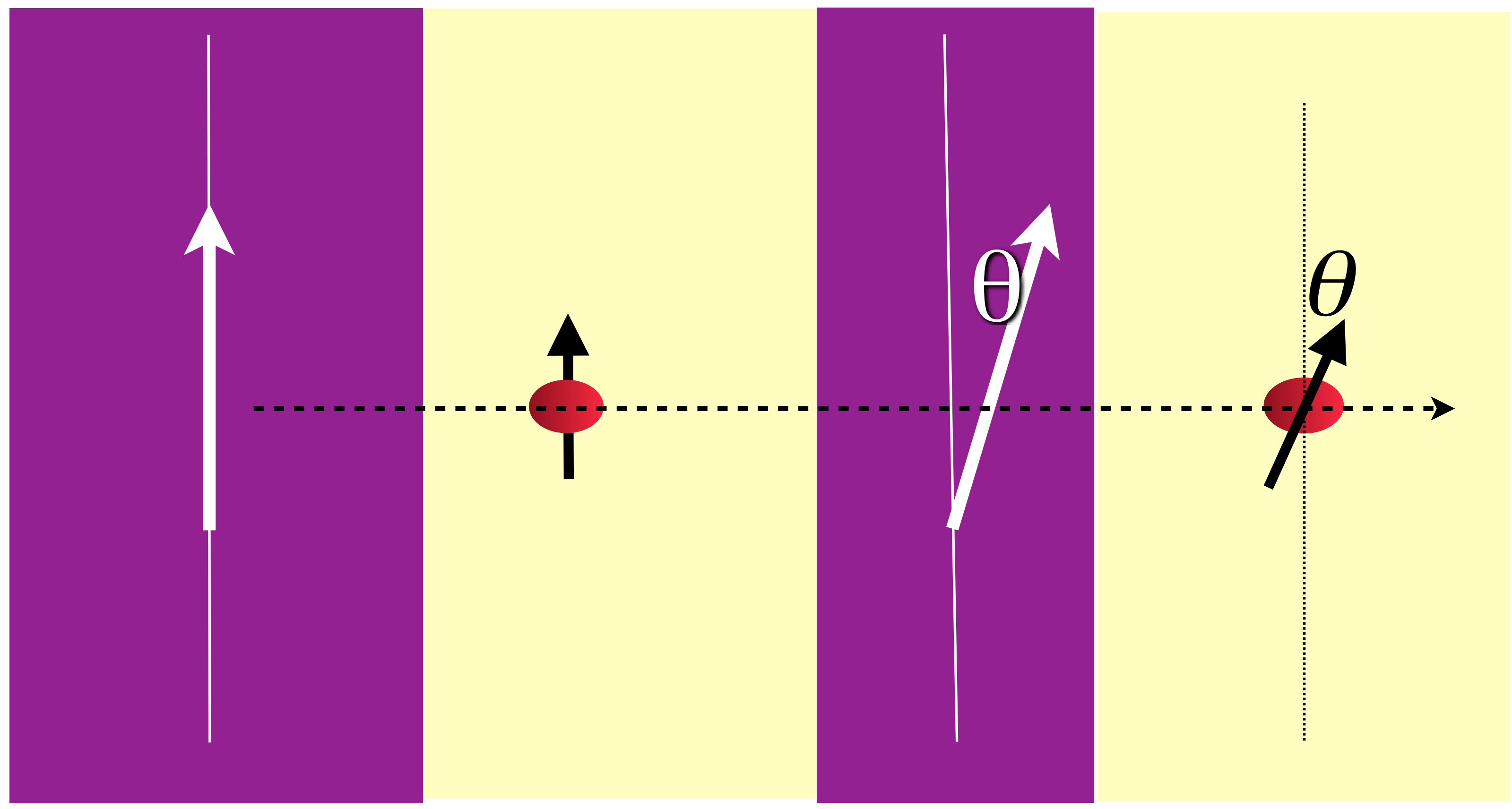
Applications: Magnetic Random Access Memory, STT-MRAM

Nature Nanotechnology, March 2015
Spin-transfer-torque memory

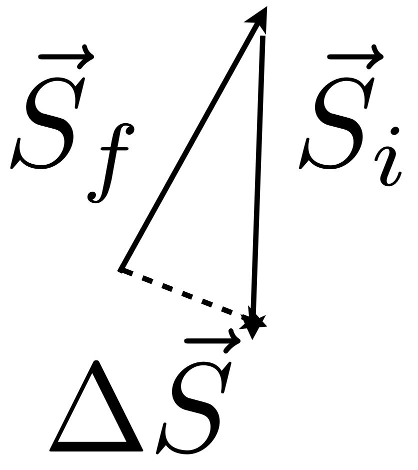
NYU

Basic Physics of Spin Transfer

Based on conservation of angular momentum



$$\frac{d\vec{S}_{\text{int}}}{dt} \rightarrow \vec{\tau}$$



$$\left|\frac{d\vec{S}_{\text{int}}}{dt}\right| = \frac{\hbar}{2e} I P \sin\theta$$

$$\frac{1}{\gamma}\frac{d\vec{M}}{dt} + \frac{d\vec{S}_{\text{int}}}{dt} = 0$$

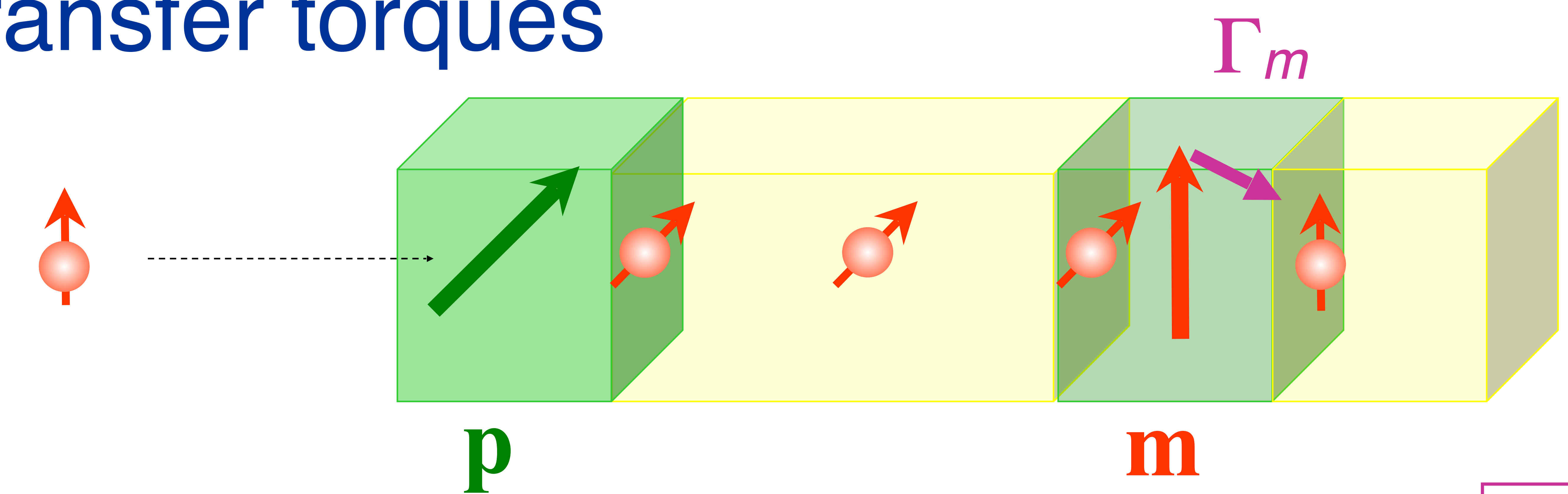
magnetization itinerant charge

- Reference layer 'sets' spin-polarization of current
- Enables readout of magnetization state through the tunnel magnetoresistance (TMR), giant magnetoresistance (GMR), or anisotropic magnetoresistance (AMR) effects

Basic Physics of Spin Transfer

Based on conservation of angular momentum

Spin transfer torques



Animation courtesy of Eric Fullerton, UCSD

Angular momentum conservation
spin transfer torques

$$\boxed{\Gamma_m = \frac{dS_{\text{int}}}{dt}}$$

All electrical (no mechanical parts) fast magnetic memory device

- Reference layer ‘sets’ spin-polarization of current
- Enables readout of magnetization state through the tunnel magnetoresistance (TMR), giant magnetoresistance (GMR), or anisotropic magnetoresistance (AMR) effects

NYU

Threshold Current for Magnetic Excitations

Switching

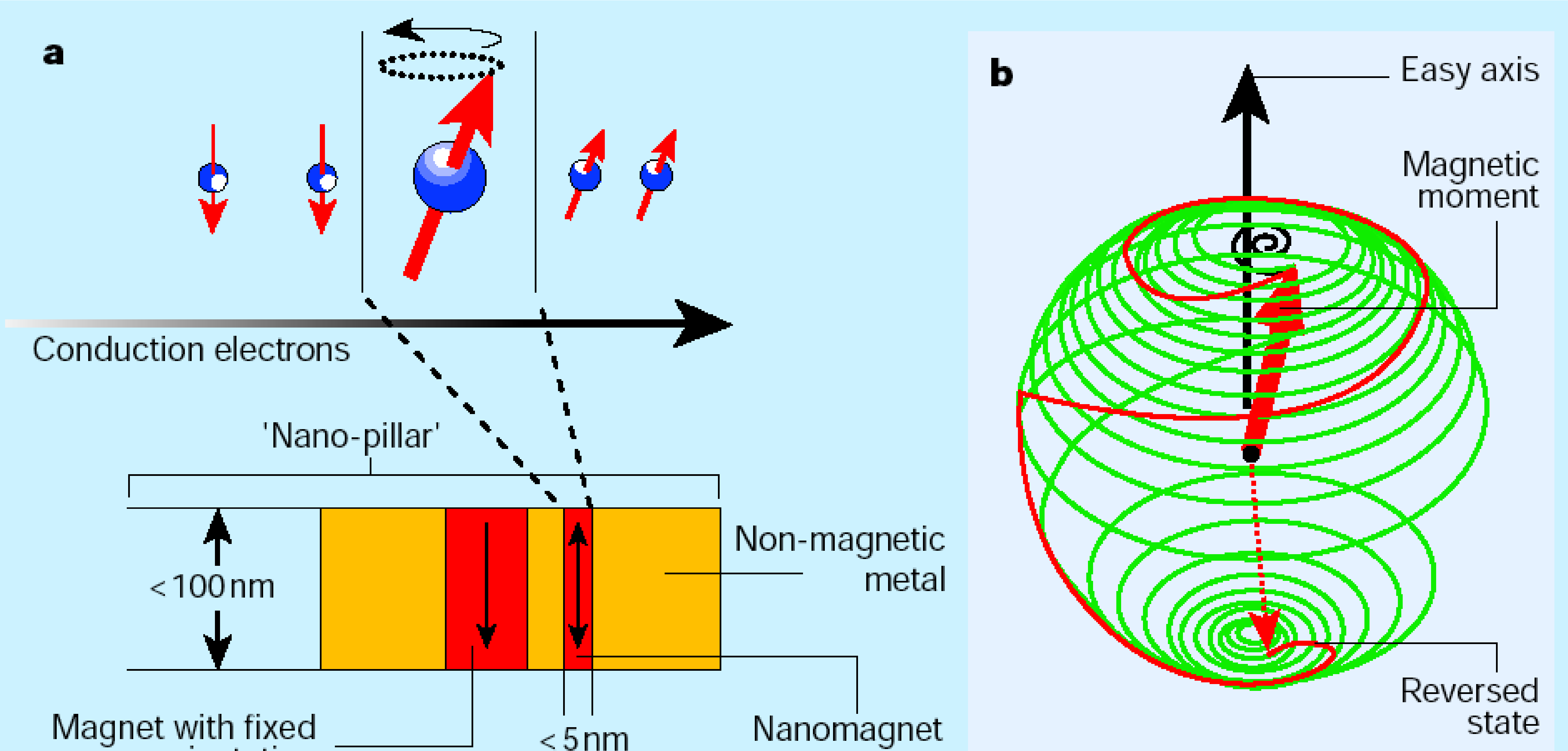
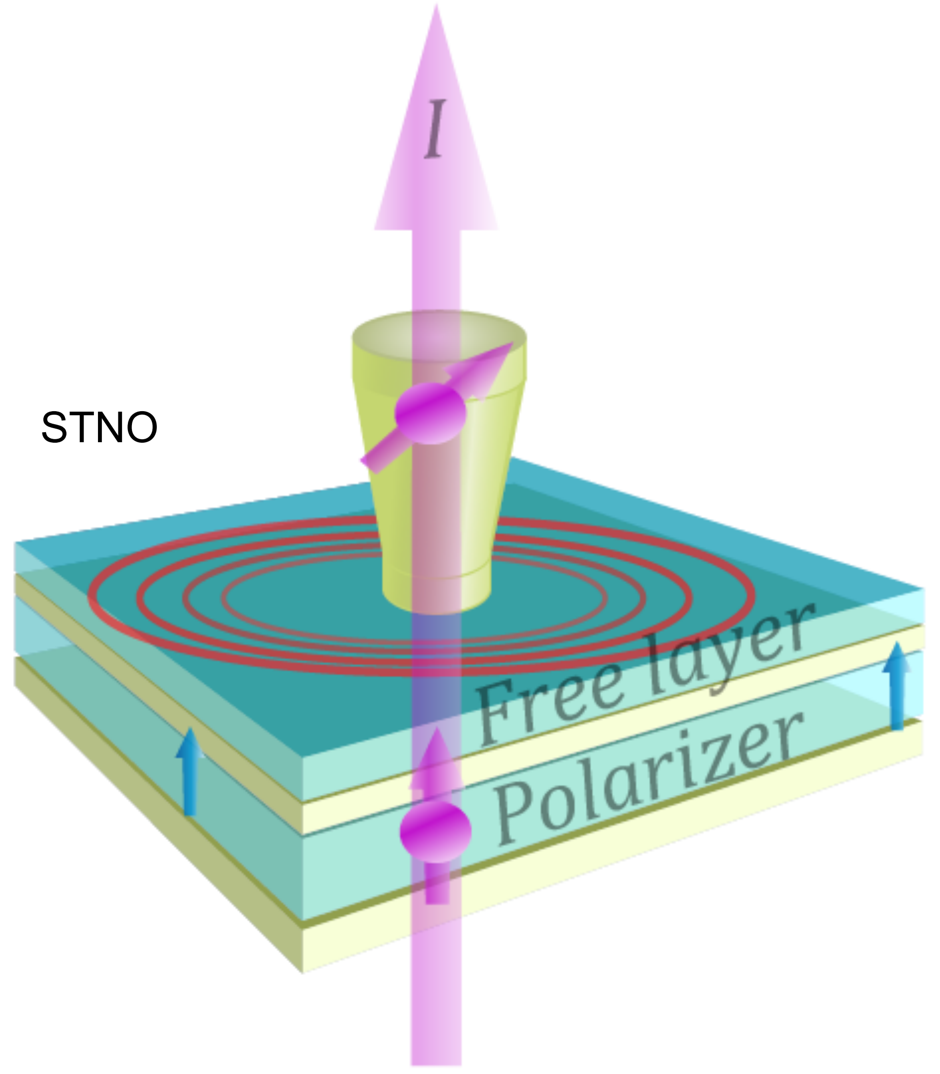
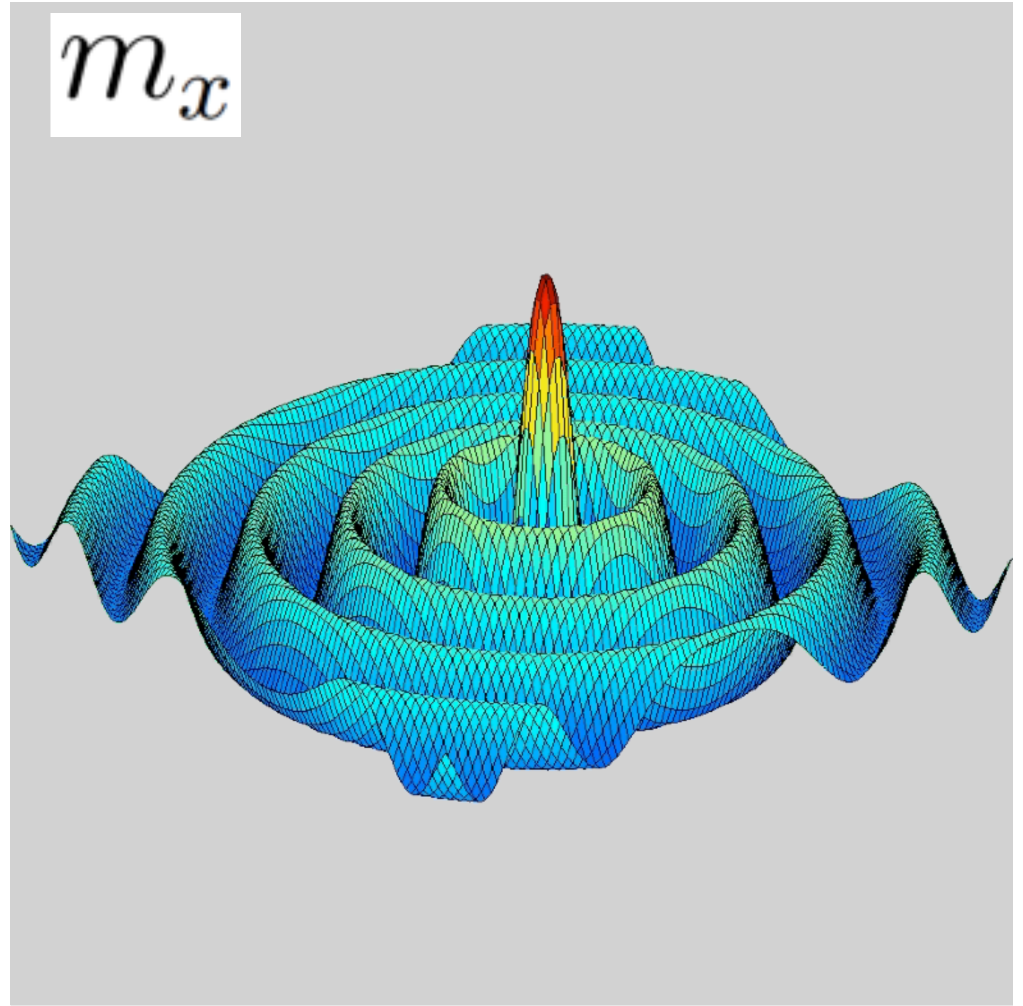


Figure courtesy of J. Z. Sun, IBM

Spin-wave excitations

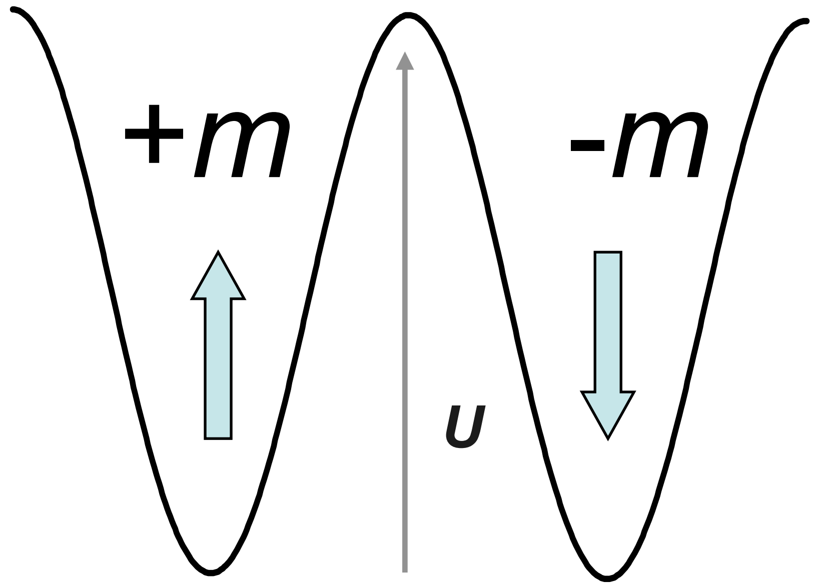




Spin-current amplifies the motion for currents greater than a critical value:

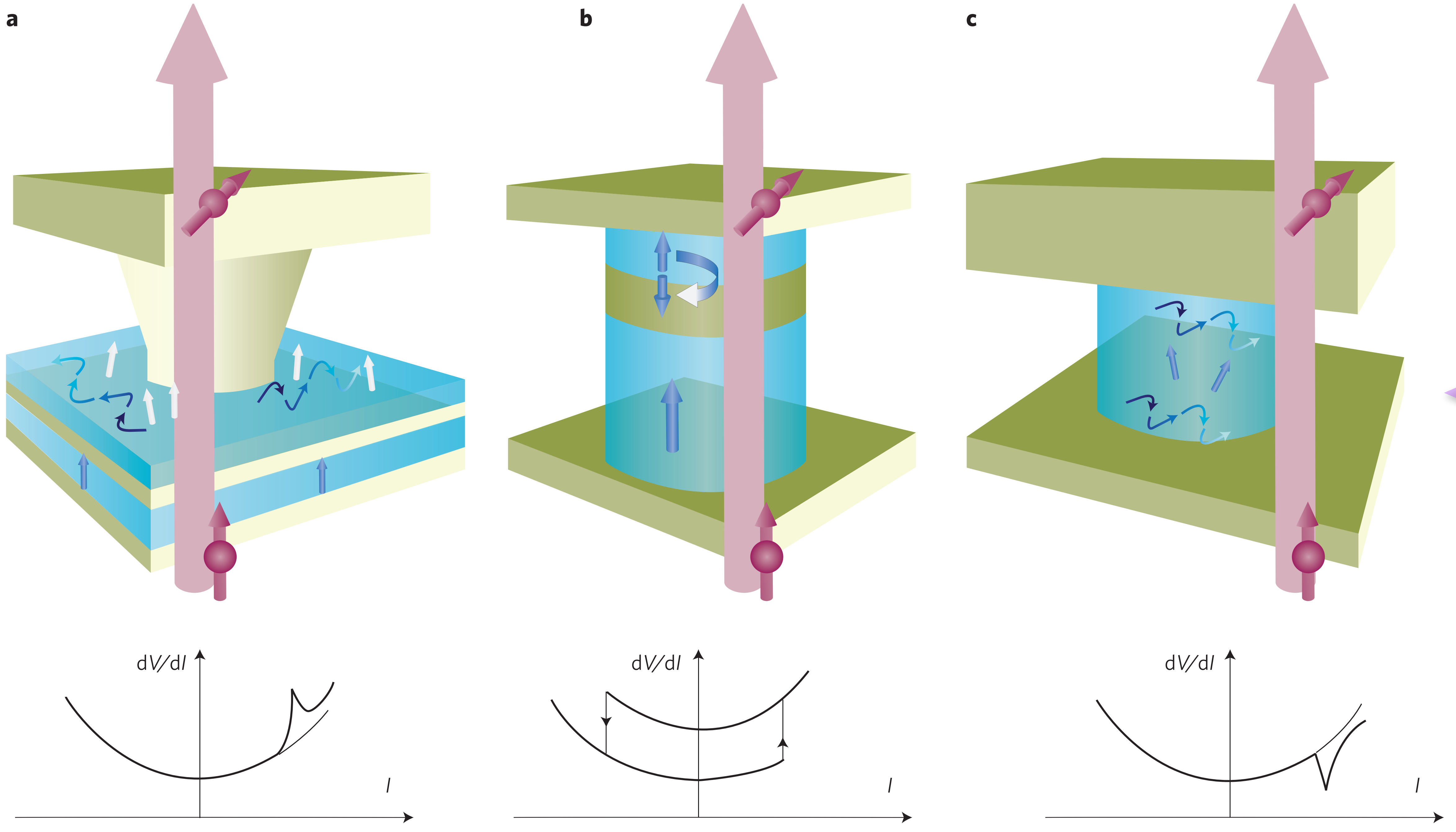
"anti-damping switching" $$I_{c0} = \frac{2e}{\hbar}\frac{\alpha}{P}\mu_0 M_s H_k V = \frac{4e}{\hbar}\frac{\alpha}{P}U$$

$$P = 1,\ \alpha = 0.01,\ U = 60kT \rightarrow I_{c0} = 15\ \mu\text{A}$$



Sample Geometries and Materials

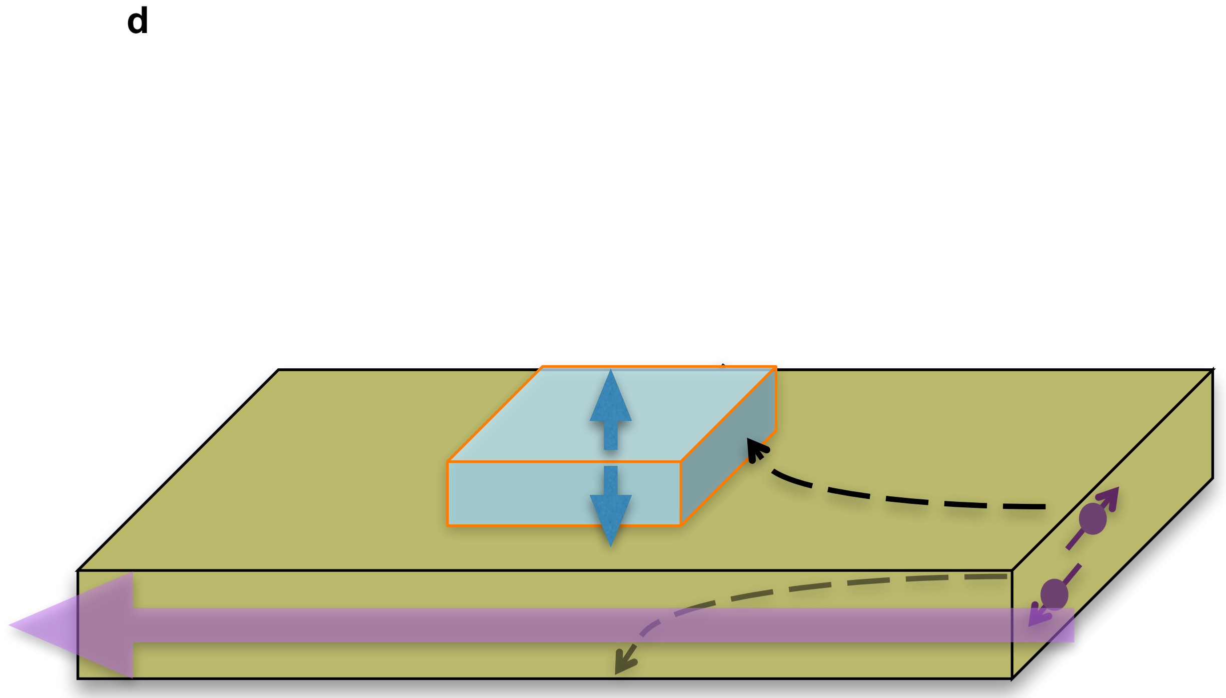
Important in nanostructures: Large current densities+STT dominate over Oersted fields



spin-torque nano-oscillators

nanopillars

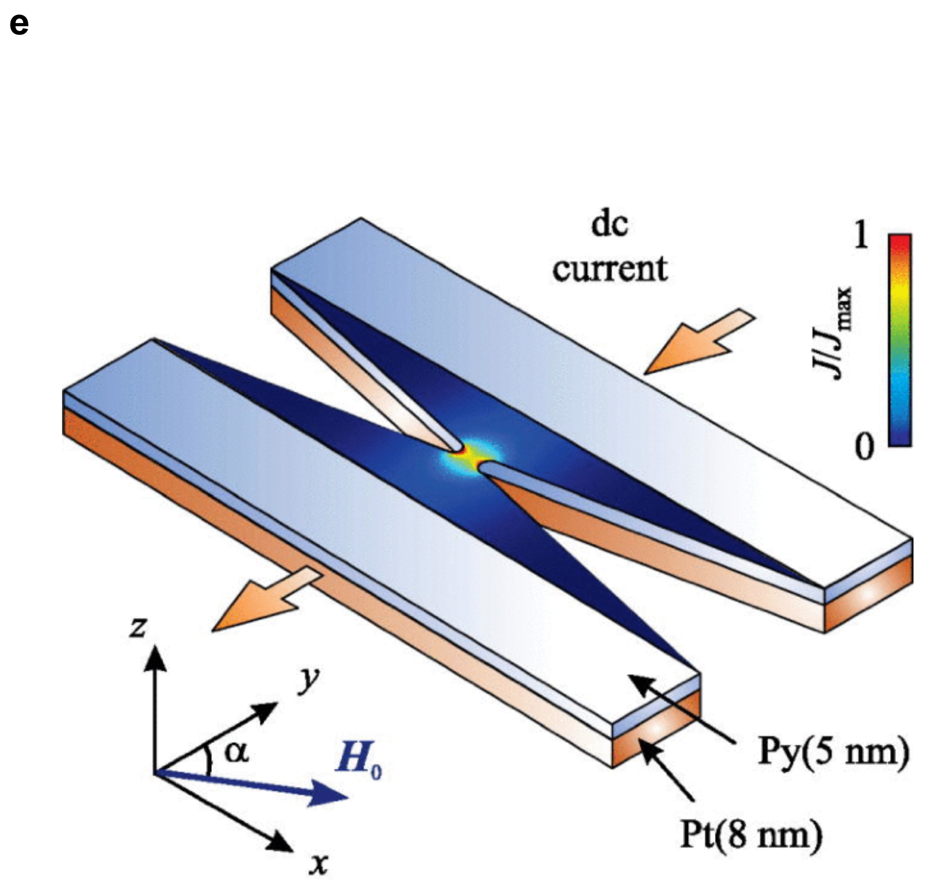
single layers



Heavy metals/Ferromagnet bilayers
M. Miron *et al.*, Nature Materials 2010
L. Liu *et al.,* Science 2012

Topological Insulators/FM
A. R. Mellnik *et al.*, Science 2014
Y. Fan *et al.*, Nature Materials 2014

spin-orbit torques



V. E. Demidov et al.
APL 105, 172410 (2014)

spin-orbit torque nanoconstriction

from: A. Brataas, ADK, H. Ohno, Nature Materials 2012

$$\frac{d\hat{m}}{dt} = \gamma\mu_0 \hat{m} \times \vec{H}_{\text{eff}} + \underbrace{\alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma a_J \hat{m} \times (\hat{m} \times \hat{p})}$$

STT can compensate damping in regions in the material

Physics and Applications of Spin-Transfer Torques

Outline

- Magnetic tunnel junctions and spin-transfer torques
- **Applications**
- Switching of magnetization, materials and device optimization
- Cryogenic applications

nature materials

LETTERS

PUBLISHED ONLINE: 11 JULY 2010 | DOI: 10.1038/NMAT2804

A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction

S. Ikeda[1,2]*, K. Miura[1,2,3], H. Yamamoto[1,2,3], K. Mizunuma[2], H. D. Gan[1], M. Endo[2], S. Kanai[2], J. Hayakawa[3], F. Matsukura[1,2] and H. Ohno[1,2]*

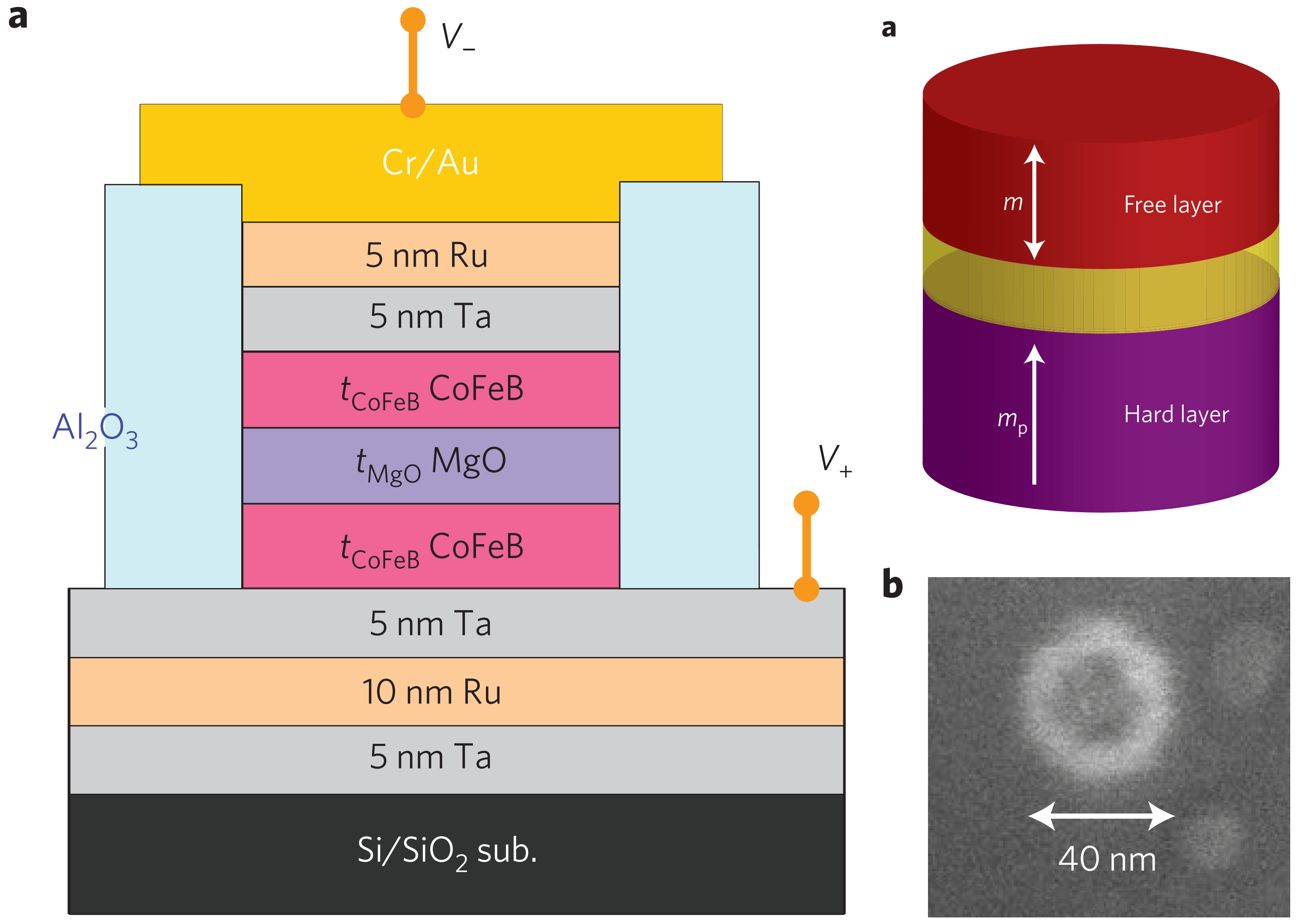
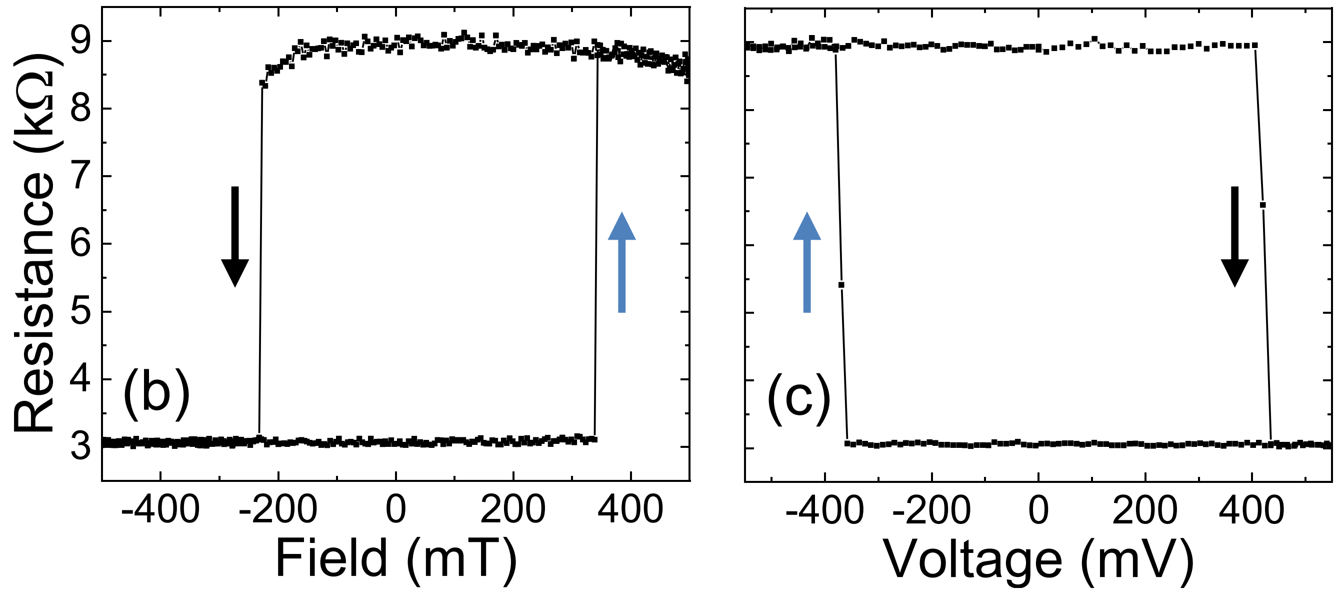


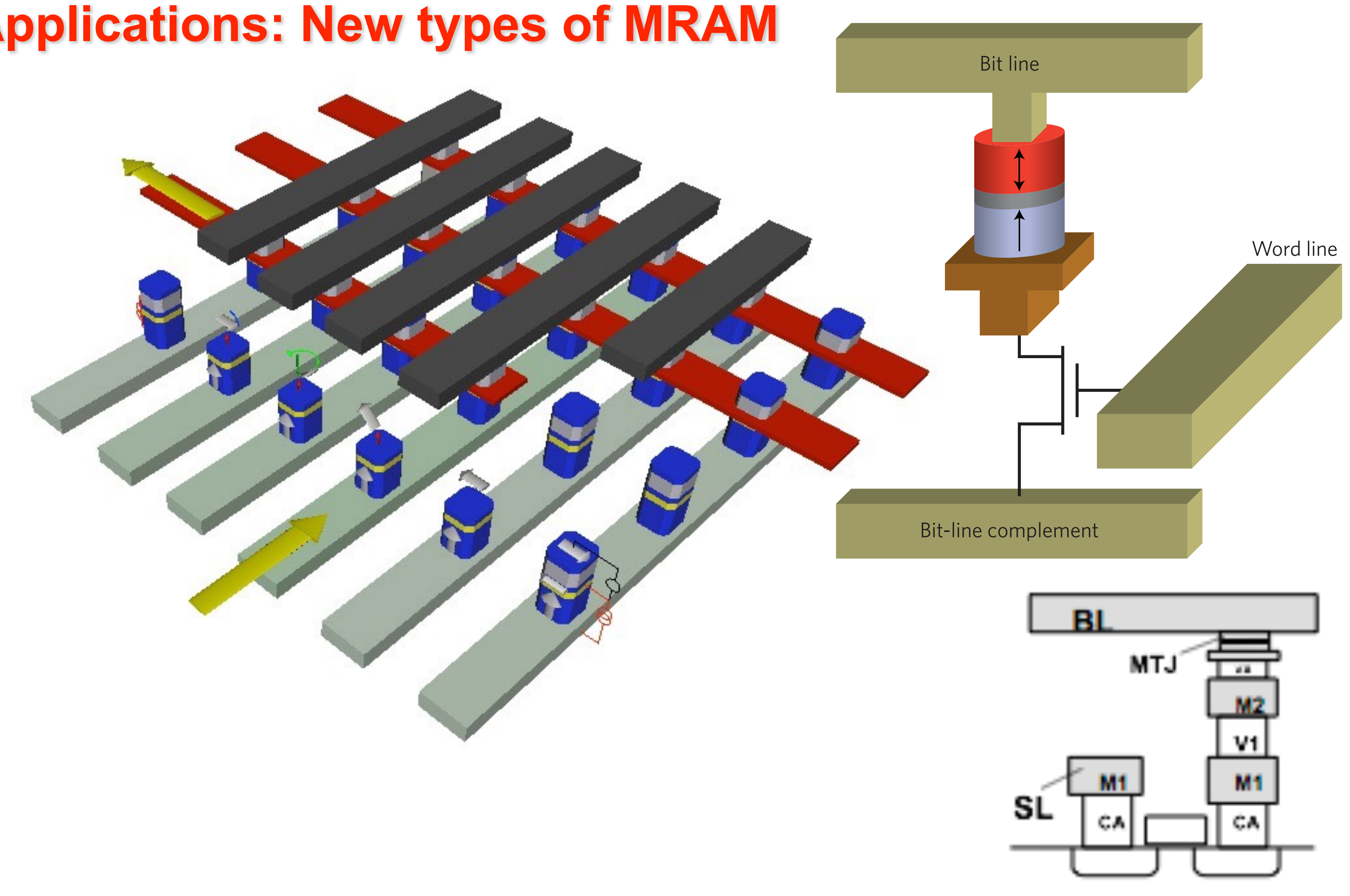
Figure 1 | MTJ structure. a, Schematic of an MTJ device for TMR and CIMS measurements. **b**, Top view of an MTJ pillar taken by scanning electron microscope.



Field induced free layer switching

Current-induced switching

Applications: New types of MRAM



R. Beach et al., IEDM 2008

Also, D.C. Worledge *et al.*, Applied Physics Letter **98**, 022501 (2011)

Perspective: A. D. Kent, Perpendicular all the way, Nature Materials **9**, 699 (2010)

Memory Comparisons

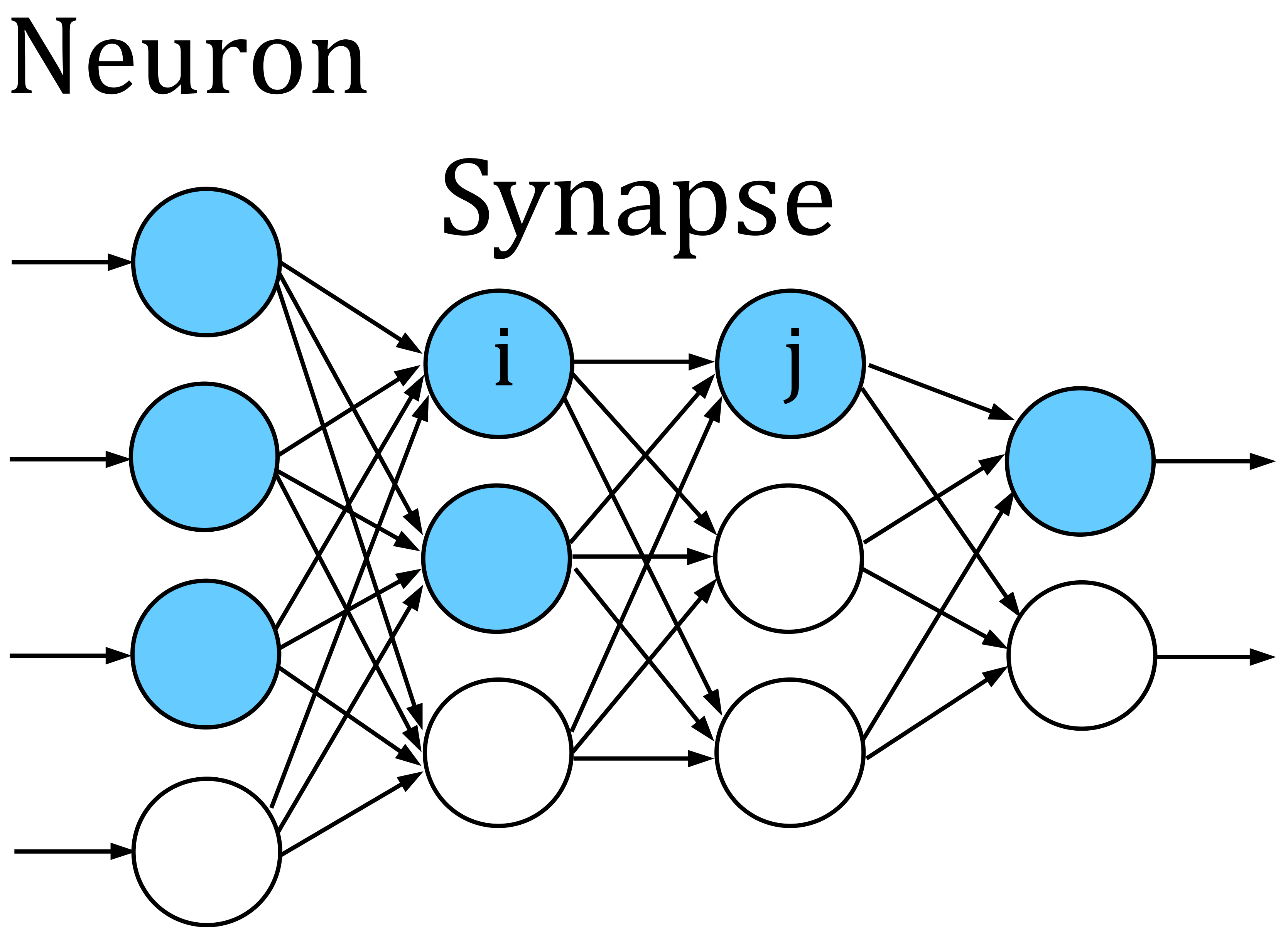
	SRAM	eDRAM	DRAM	eFlash (NOR)	Flash (NAND)	FeRAM	PCM	STT MRAM	SOT MRAM	RRAM
Endurance	Unlimited	Unlimited		10^5		10^{14}	10^9	Unlimited	Unlimited	10^9
Read/Write access time	< 1 ns	1-2 ns	30 ns	10/10^3 ns	100/10^6 ns	30 ns	10/100 ns	2-30 ns	2-30 ns	1-100 ns
Density	Low (6 transistors)	Medium		Medium	High (multiple bits/cell)	Low (limited scalability)	High (multiple bits/cell)	Medium	Medium (>STT MRAM)	High (multiple bits/cell)
Write power	Medium	Medium		High		Medium	Medium	Medium	Low	Medium
Standby power	High	Medium		Low		Low	Low	Low	Low	Low
Other	Volatile	Volatile. Refresh power and time needed.		High voltage required		Destructive readout	Operating T < 125 C	Low read signal	Fabrication challenges	Complex mechanism

Comparison of key features of existing and emerging memories. Significant disadvantages are marked in red. Estimates for emerging memories are based on expectations for functioning chips, not demonstrations of individual bits.

From A. D. Kent and D. C. Worledge, “A new spin on magnetic memories,” Nature Nanotechnology **10**, 187 (2015)

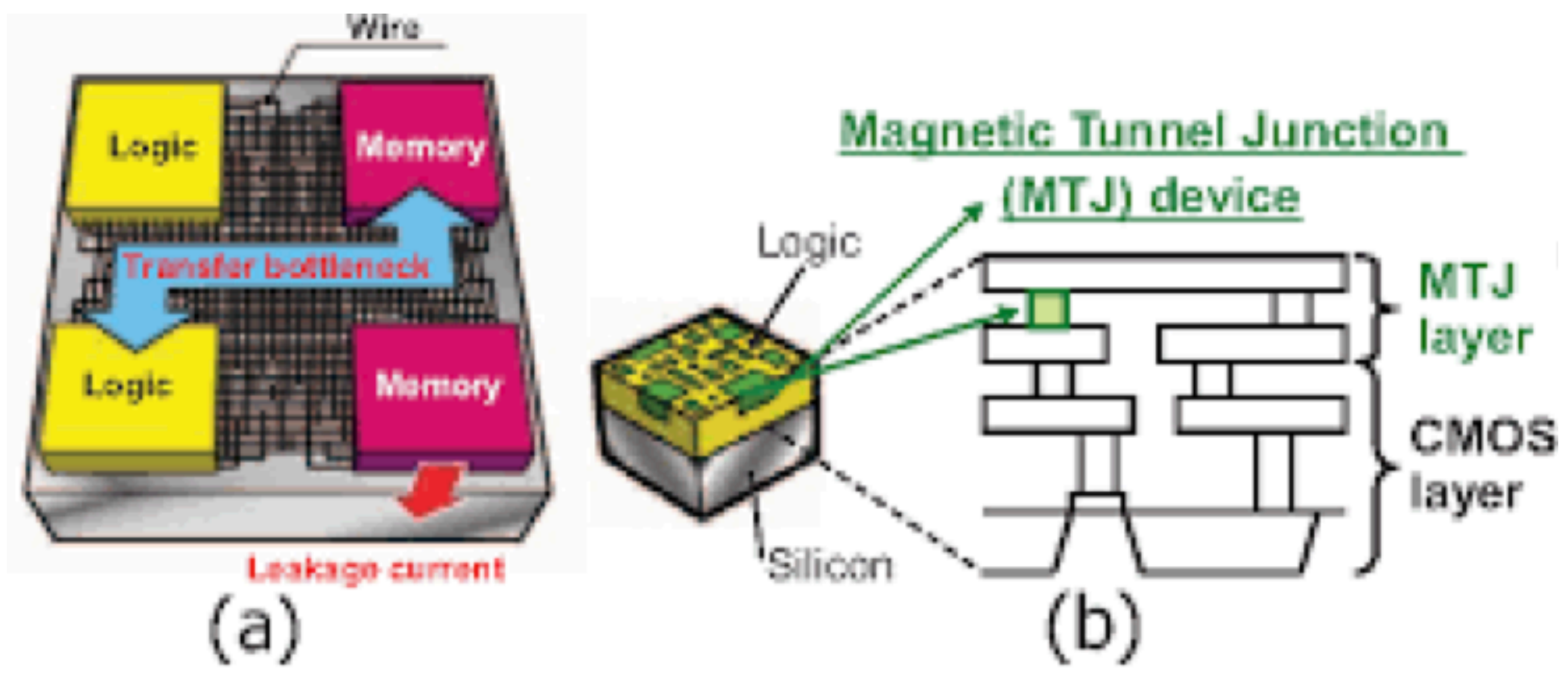
Convolutional Neural Networks

Some potential applications of MTJs



Spin transfer torque magnetic random access memory used to store weights in a convolutional neural network

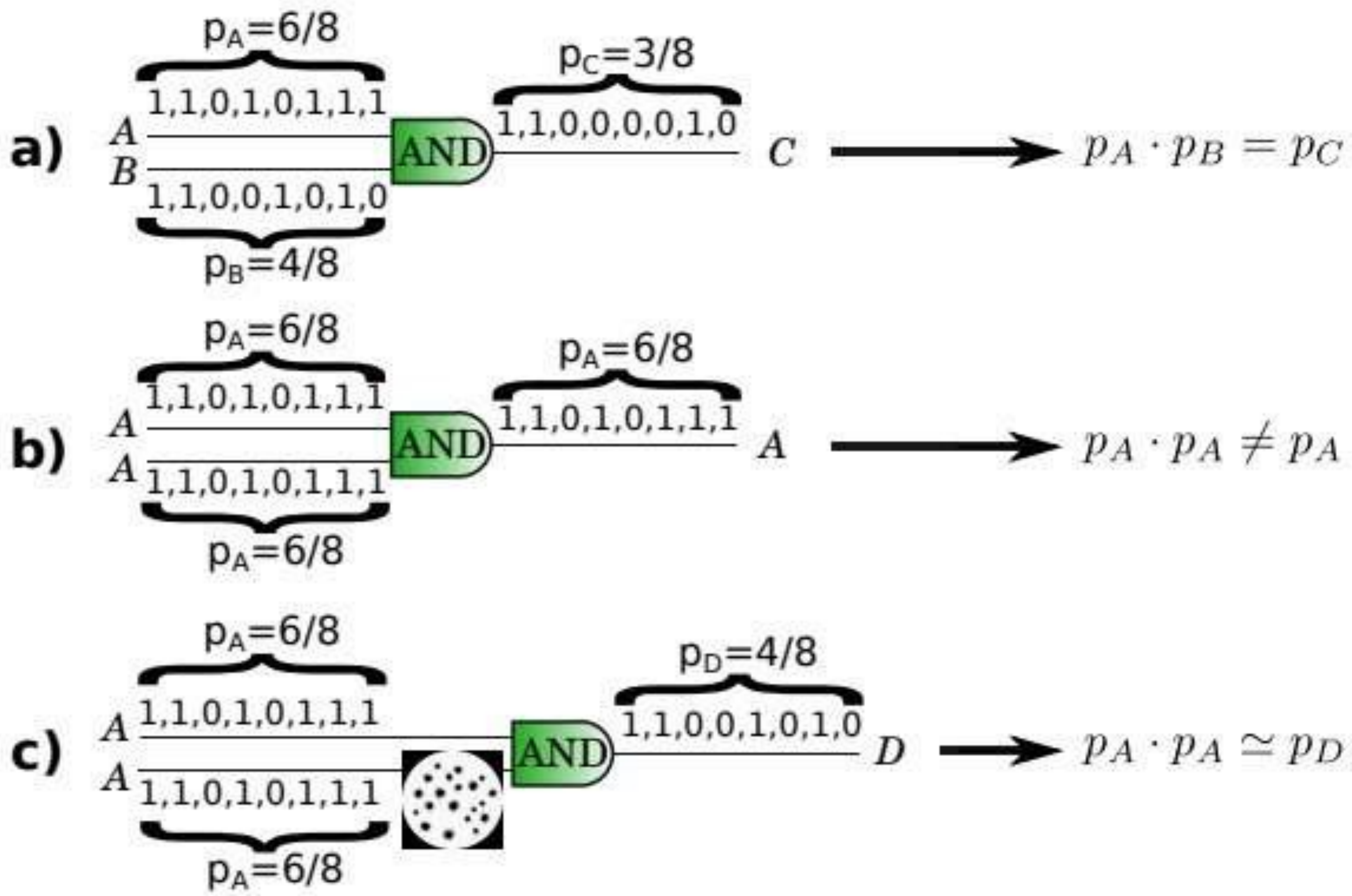
-Persistent (i.e. nonvolatile)
-Energy needed only for write/read
-Closely integrated with logic elements



From: T. Hanyu et al., Design, Automation & Test in Europe Conference 2015
DOI:10.7873/date.2015.1119

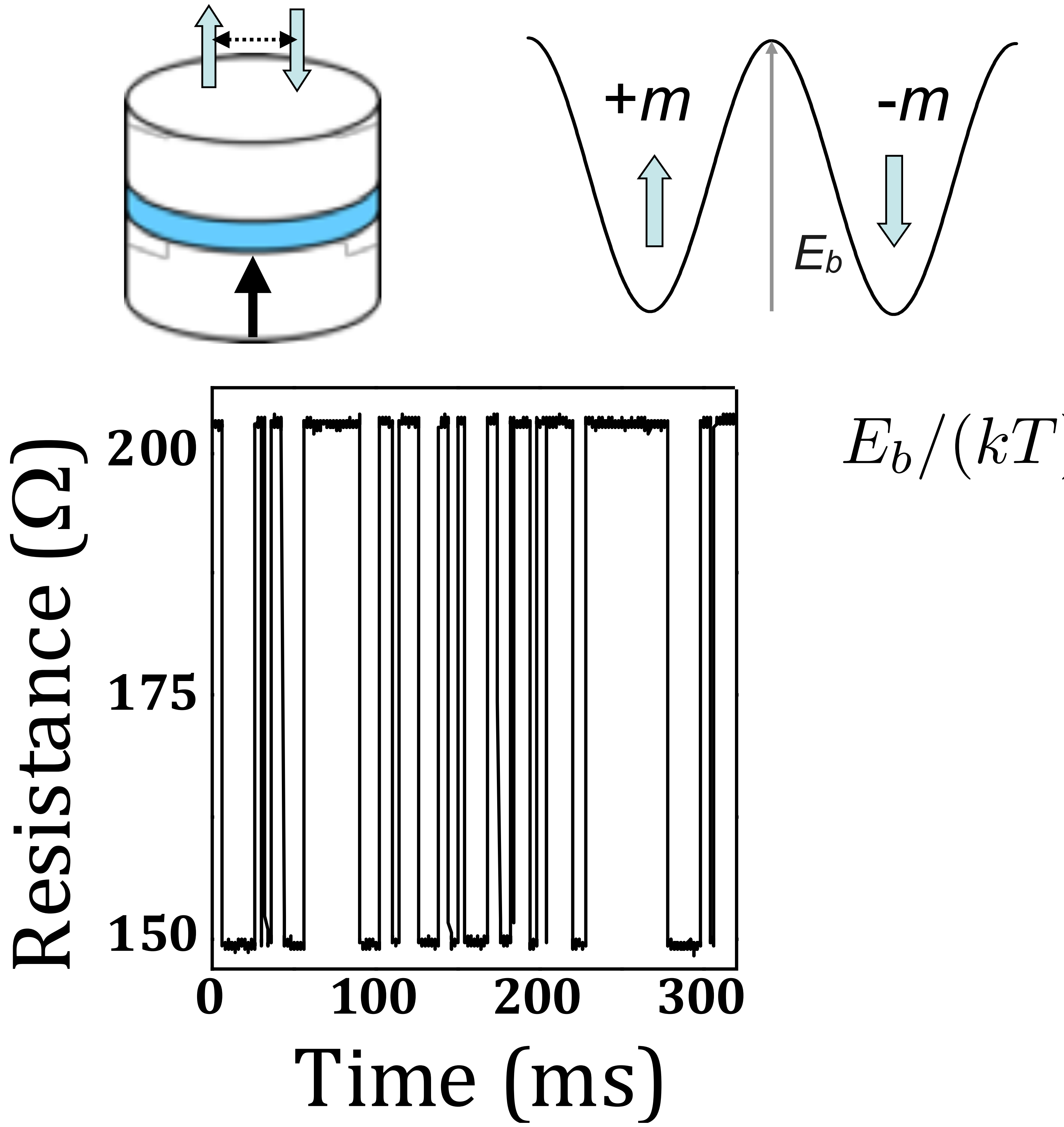
Stochastic Computing

Approximate computing



D. Pinna *et al.*, Phys. Rev. Applied 9, 064018 (2018)

MTJ random number generator



$E_b/(kT) \lesssim 20$

Spin transfer and spin-orbit torques can set:

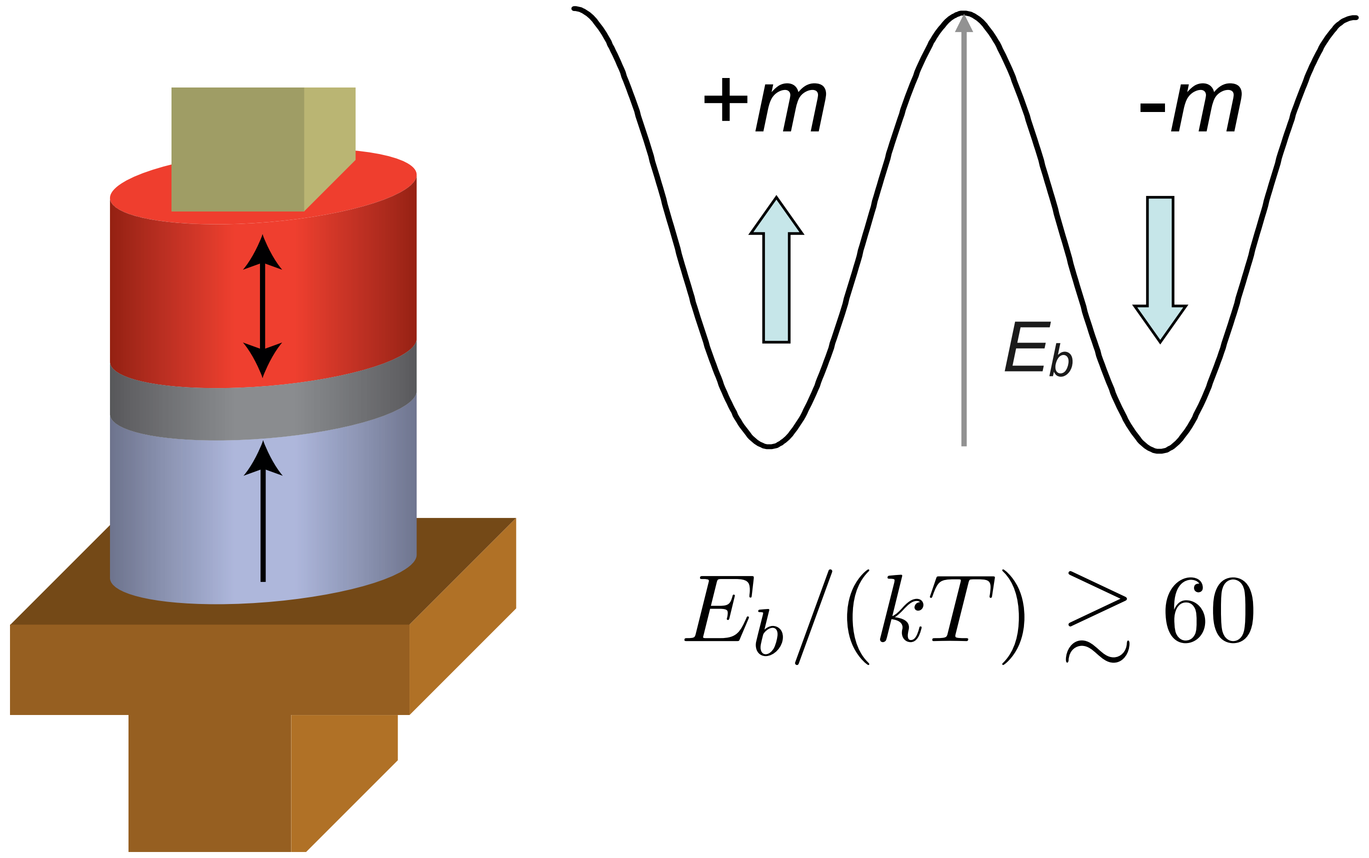
- Probabilities
- Time scales

Physics and Applications of Spin-Transfer Torques

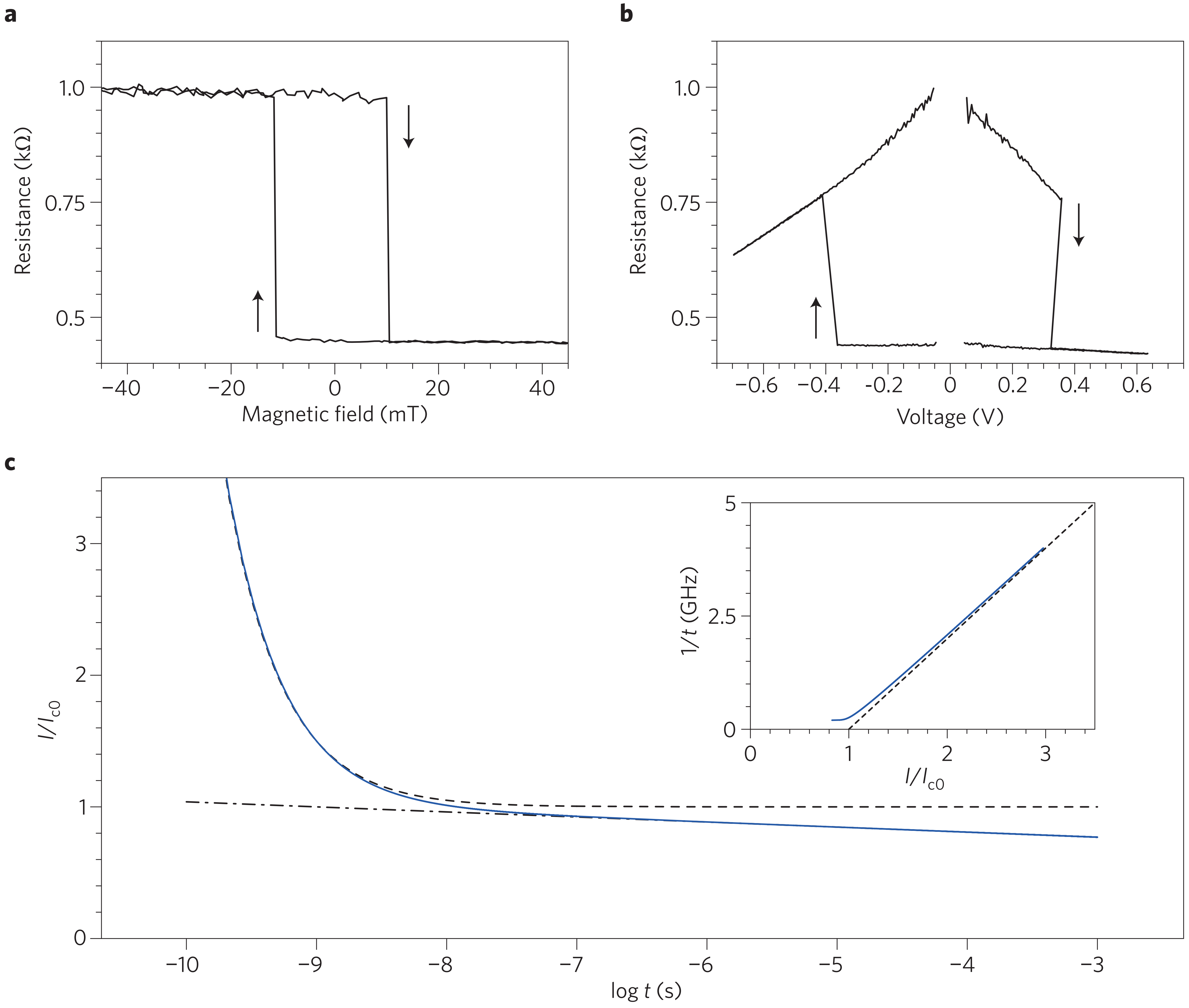
Outline

- Magnetic tunnel junctions and spin-transfer torques
- Applications
- **Switching of magnetization, materials and device optimization**
- Cryogenic applications

Magnetic Tunnel Junction



$$E_b/(kT) \gtrsim 60$$

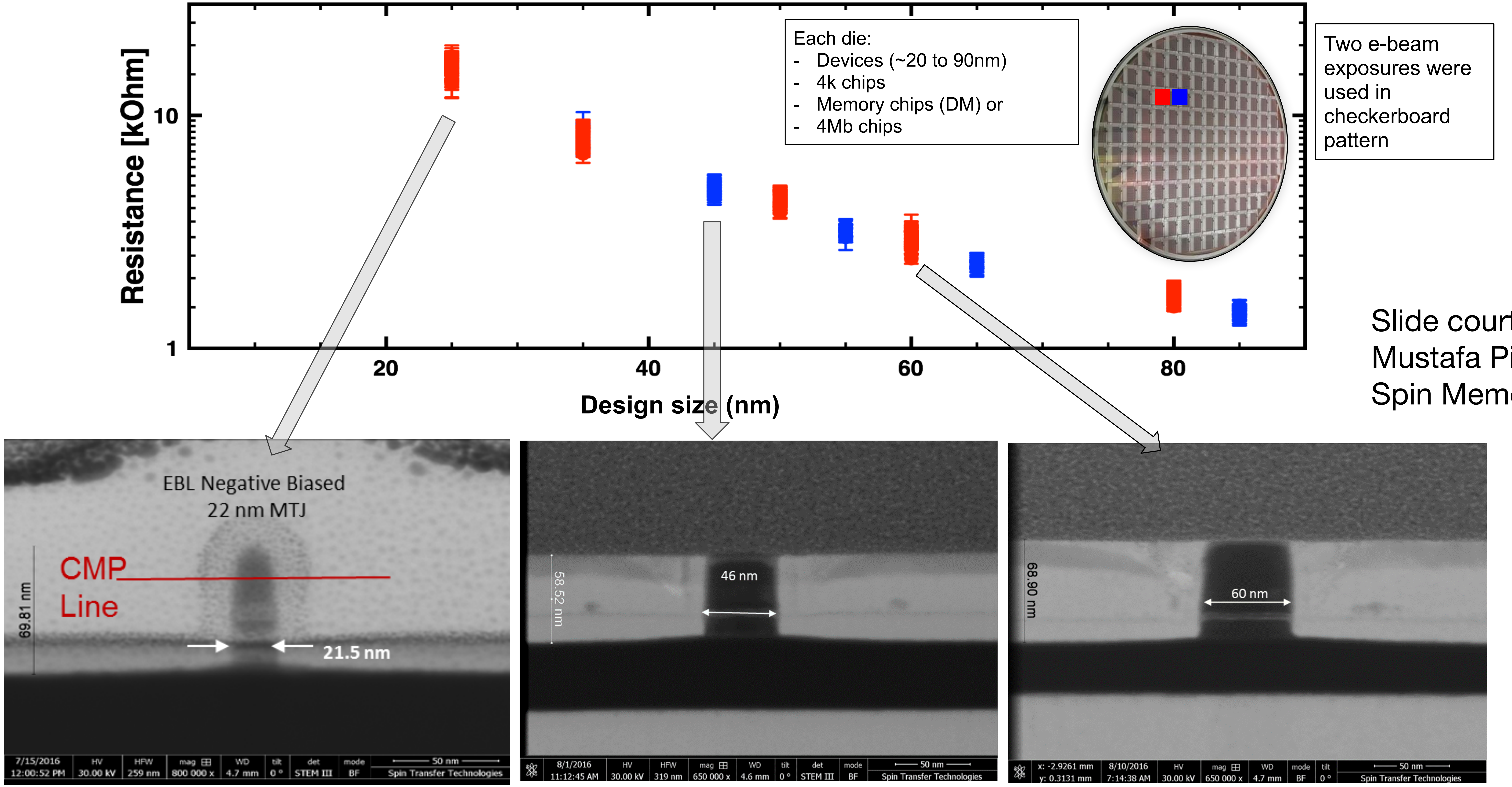


A. D. Kent and D. C. Worledge, “A new spin on magnetic memories,” Nature Nanotechnology **10**, 187 (2015)

MRAM Technology Development at Spin Memory

MTJ nanopillars for Gbit density arrays

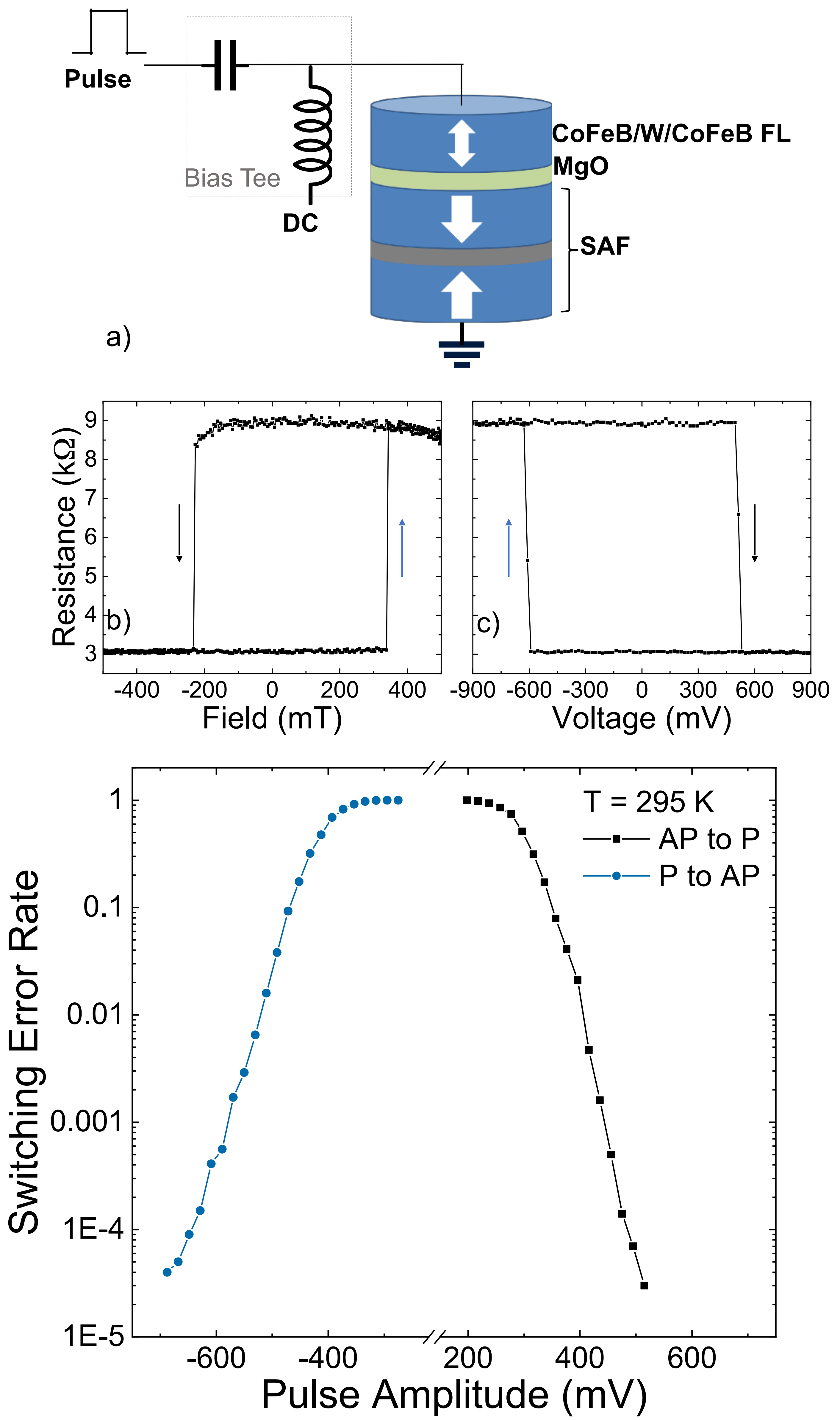
- Scaling down to 20 nm diameters

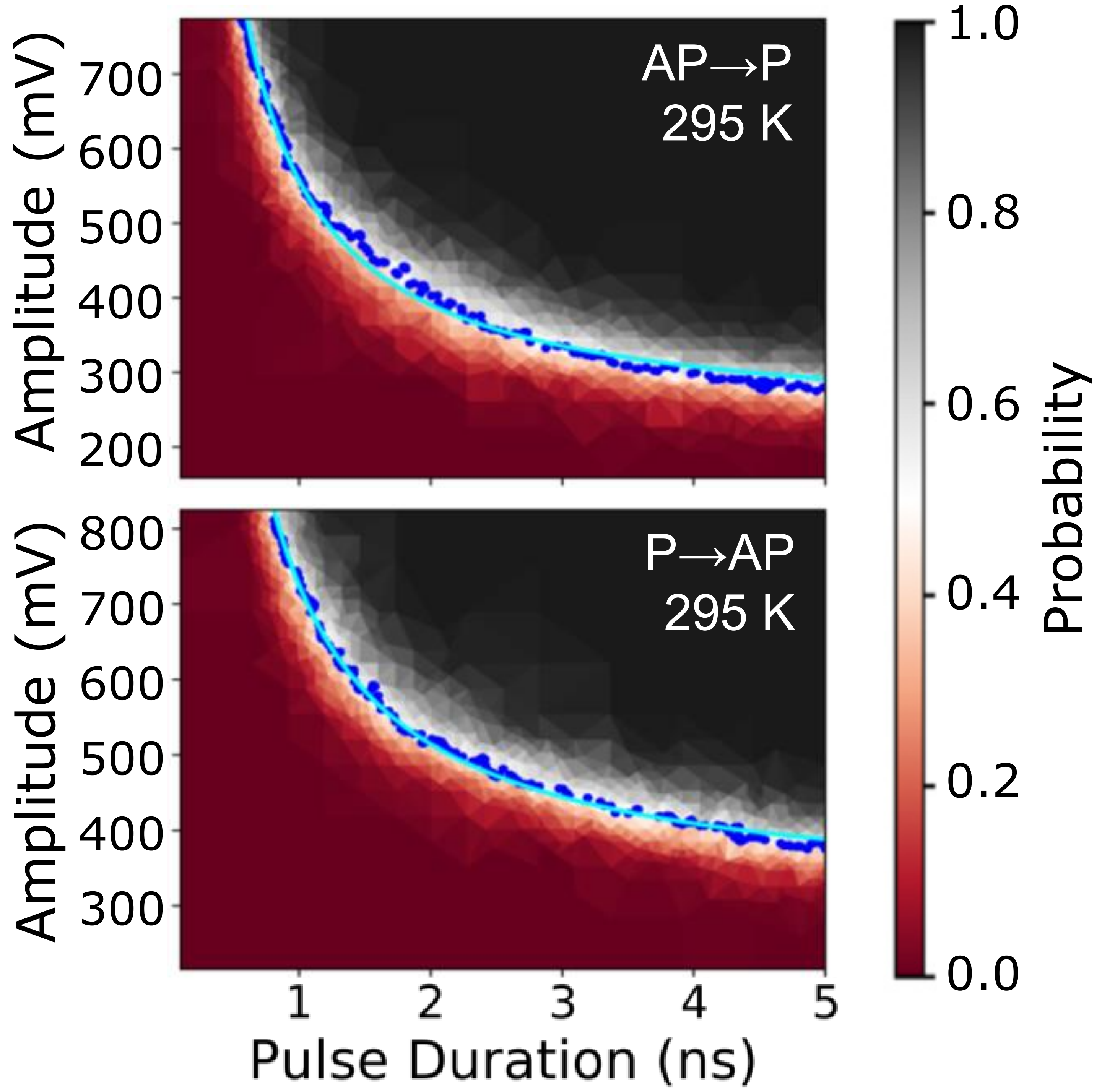


Slide courtesy of Mustafa Pinarbasi, CTO, Spin Memory

High Speed Magnetization Switching

40 nm diameter nanopillar





$$\frac{1}{\tau} = \frac{1}{\tau_0}\left(\frac{I - I_c}{I_c}\right)$$

$$\tau_0 I_c = I\tau - I_c\tau$$

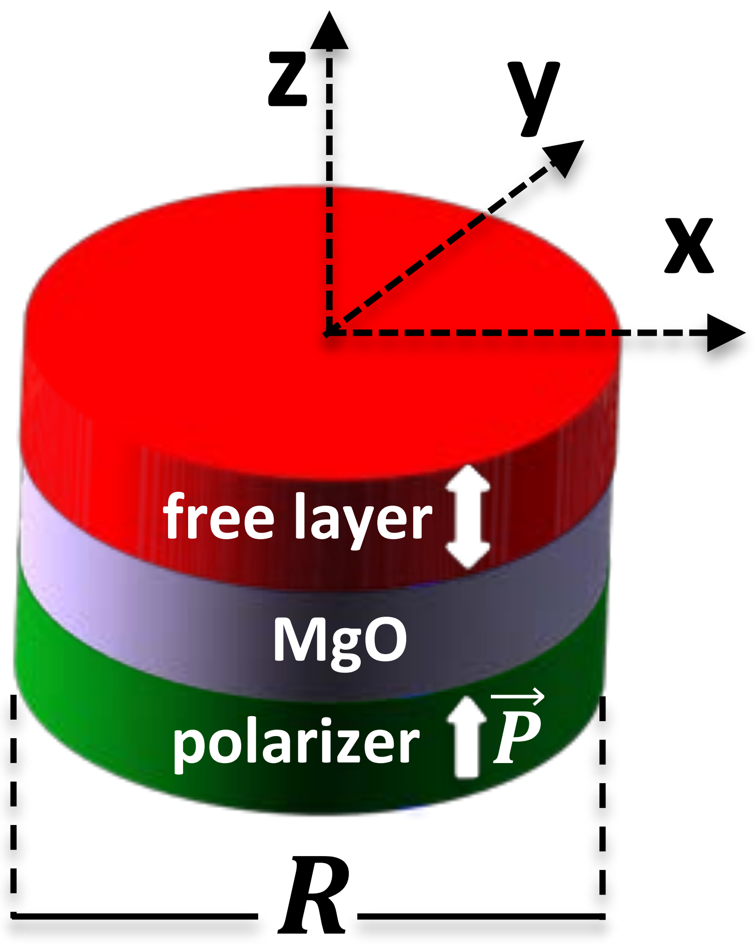
const. N dissipation

Write energy: $\lesssim 250\ \mathrm{fJ}$

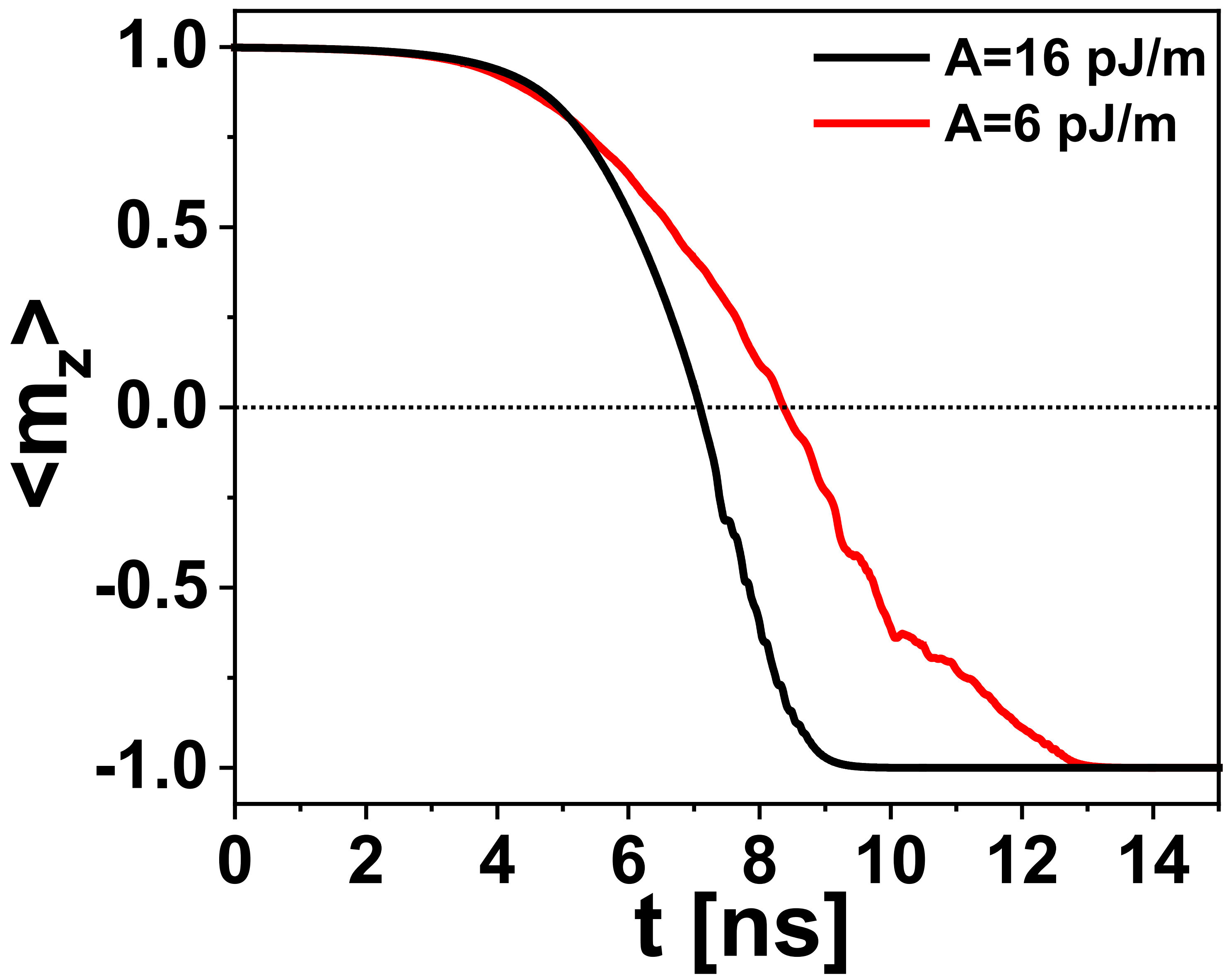
Laura Rehm *et al.*, APL **115**, 182404 (2019)

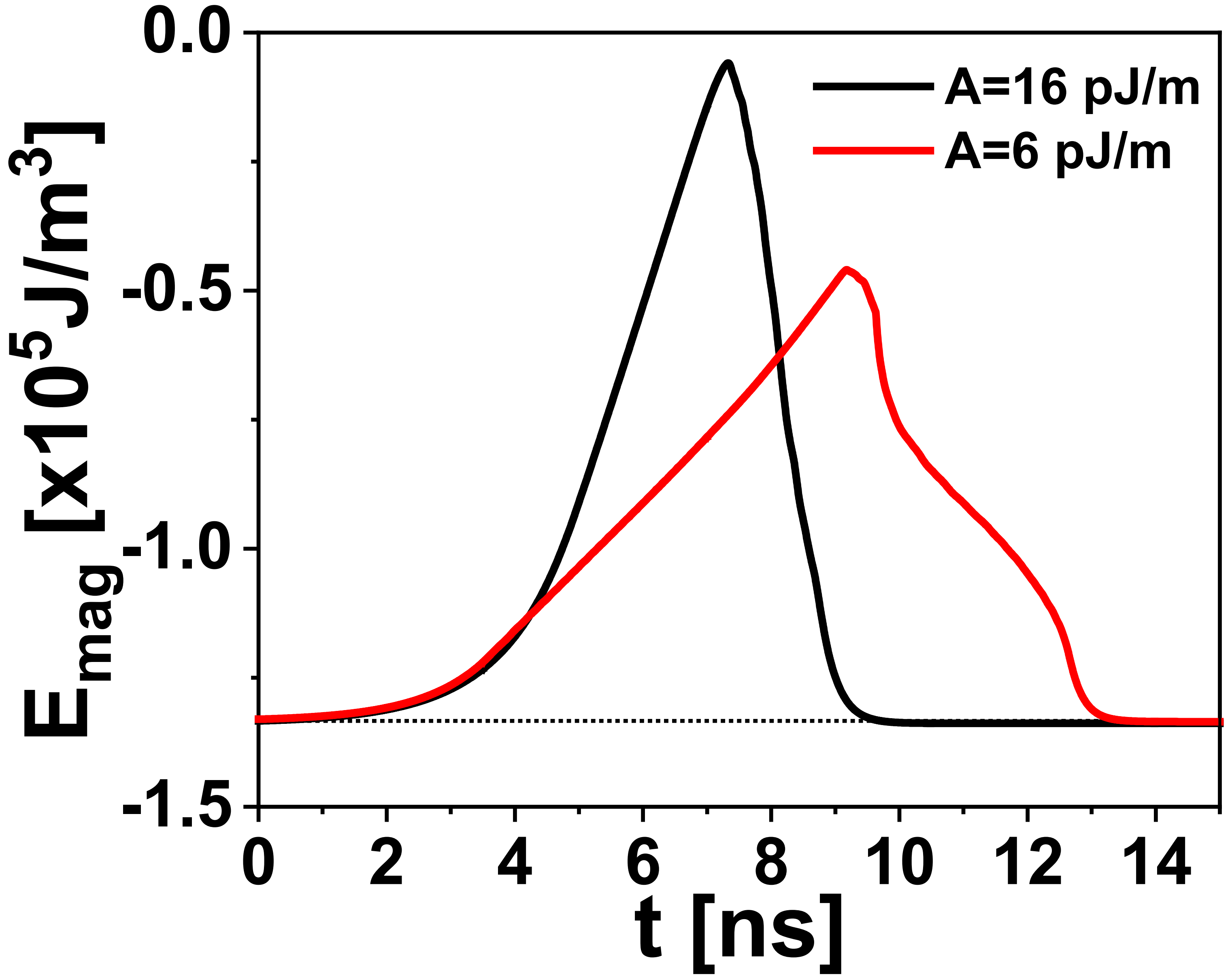
Magnetic Anisotropy and Exchange Energy

- Set the length scales for spatial variation of the magnetization
- Determines the energy barrier for thermally activated magnetization reversal and affects the **switching time**



$R = 100$ nm
$J/J_{c0} = 1.6$



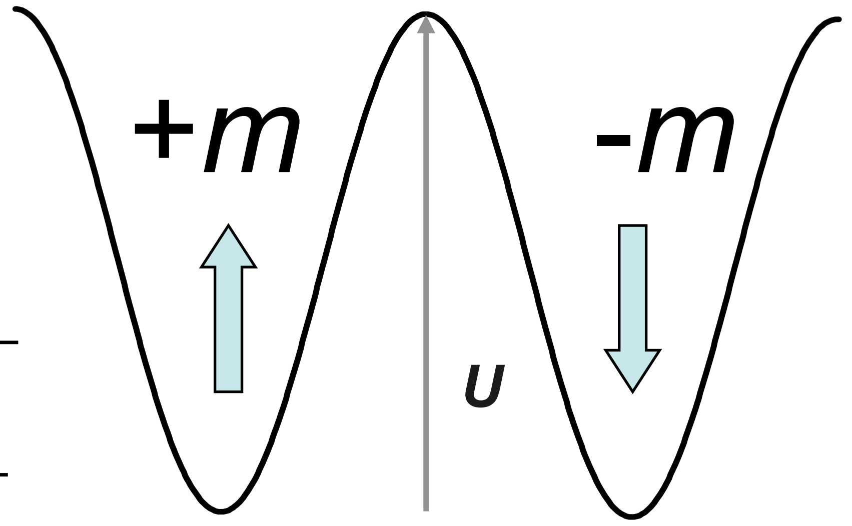


Effective anisotropy: $\mu_0 M_{\text{eff}} = 0.3$ T
Exchange constant: $A = 16$ pJ/m

domain wall width: $\Delta = 20$ nm

Magnetic Anisotropy and Exchange Energy

- Set the length scales for spatial variation of the magnetization
- Determines the **energy barrier for thermally activated magnetization reversal** and affects the switching time



$$d_c = \frac{16}{\pi}\sqrt{\frac{A}{K_{\mathrm{eff}}(d)}}$$

$$d \le d_c \qquad U = K_{\mathrm{eff}}\frac{\pi}{4}d^2 t$$

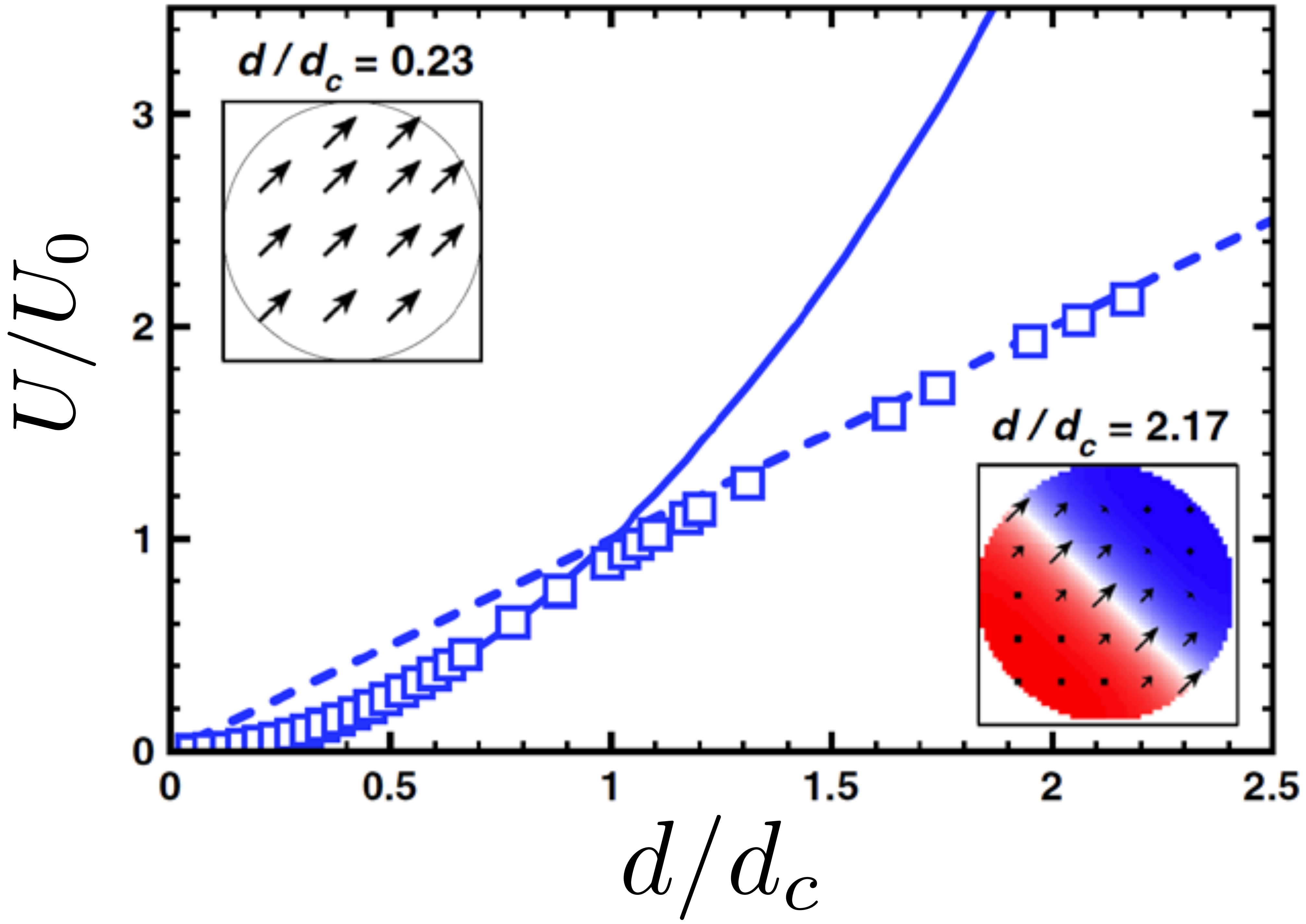
$$d > d_c \qquad U = 4\sqrt{AK_{\mathrm{eff}}}\,dt$$

A : exchange constant

K_{eff} : effective perpendicular anisotropy

d : diameter of the element

t : thickness



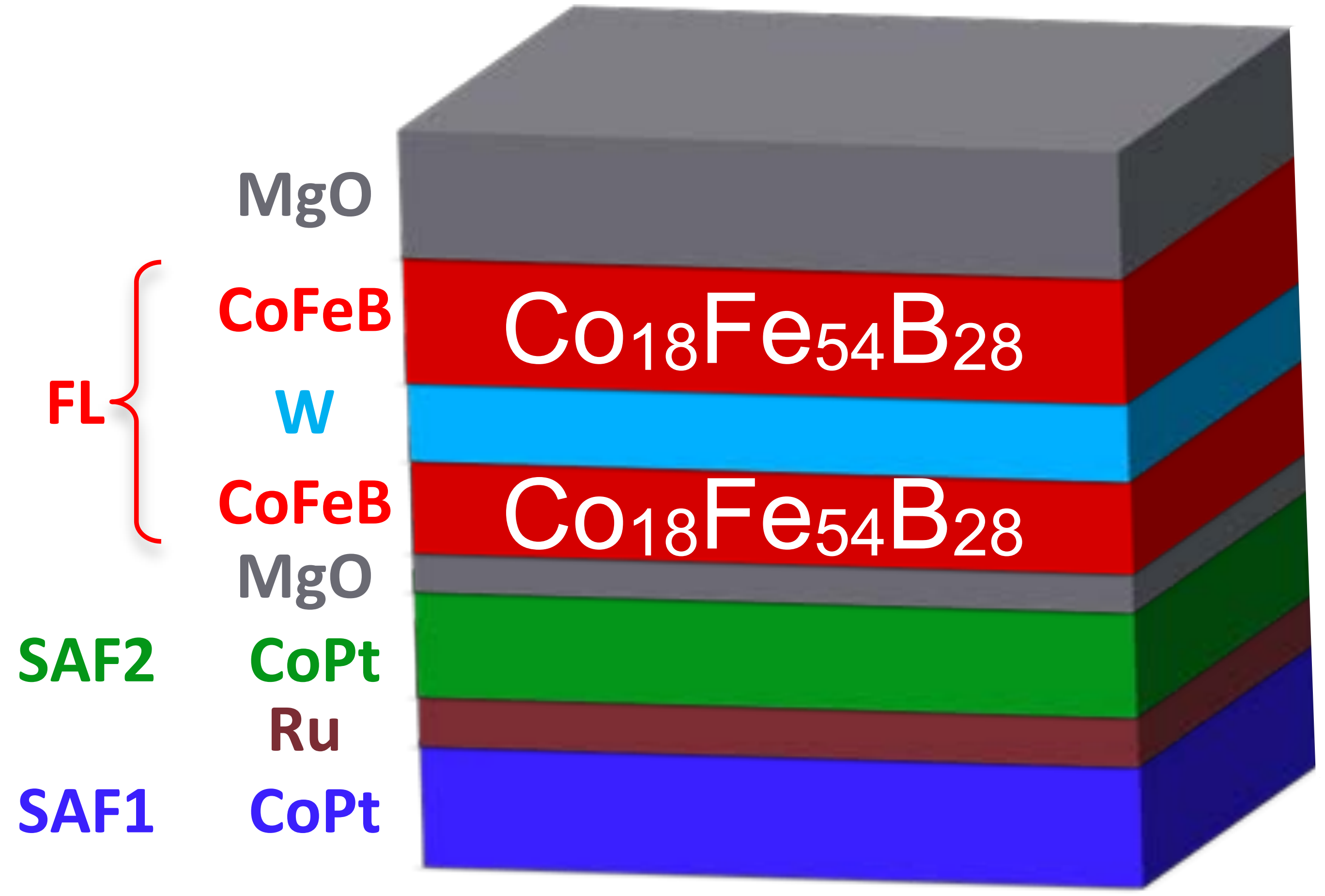
Gabriel D. Chaves-O'Flynn *et al.*, Phys. Rev. Applied **4,** 024010 (2015)

Experiment: L. Thomas *et al.*, IEDM 15-673 (2015)

Magnetic Anisotropy and Exchange Energy

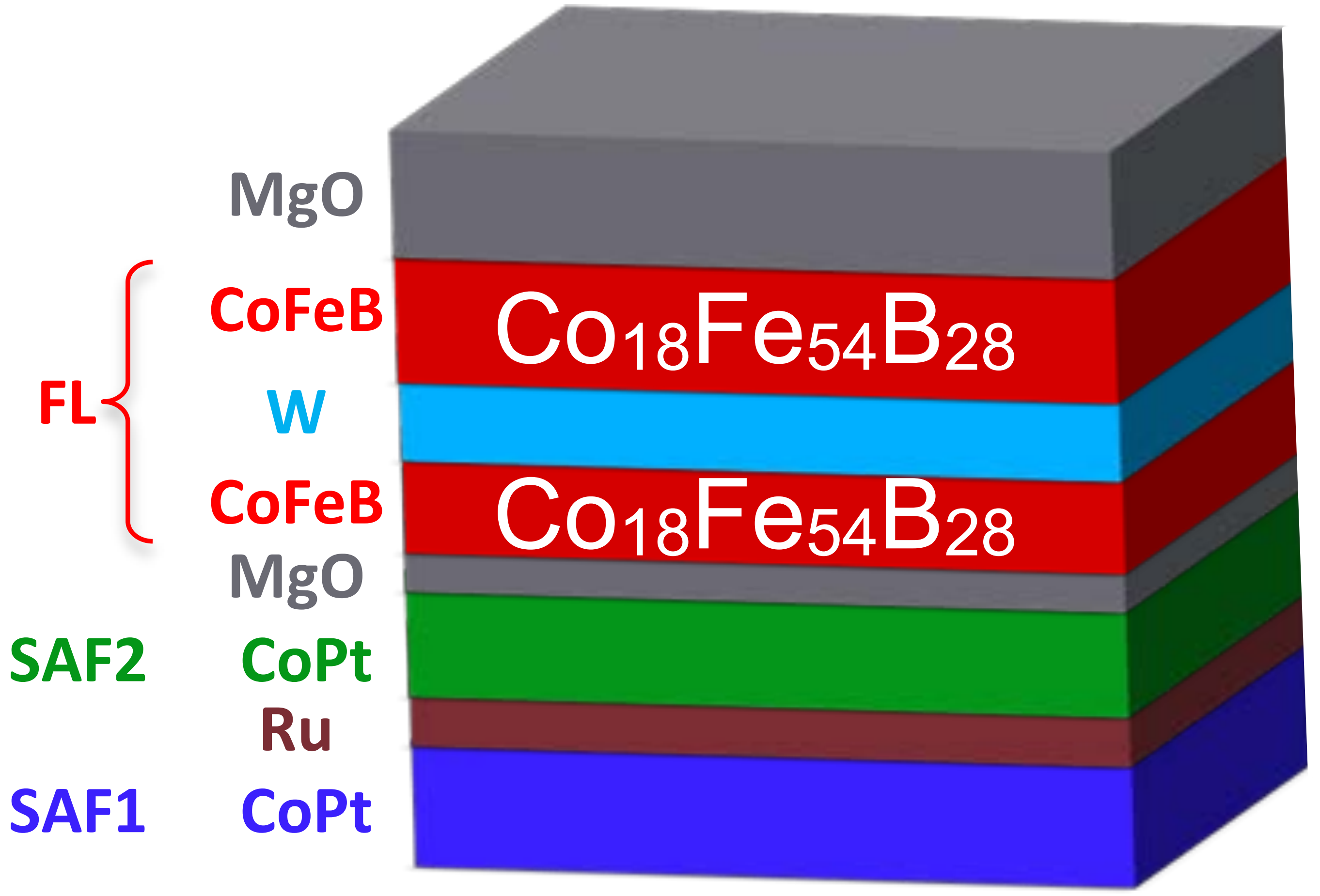
- **Free layer in pMTJ are composite layers**

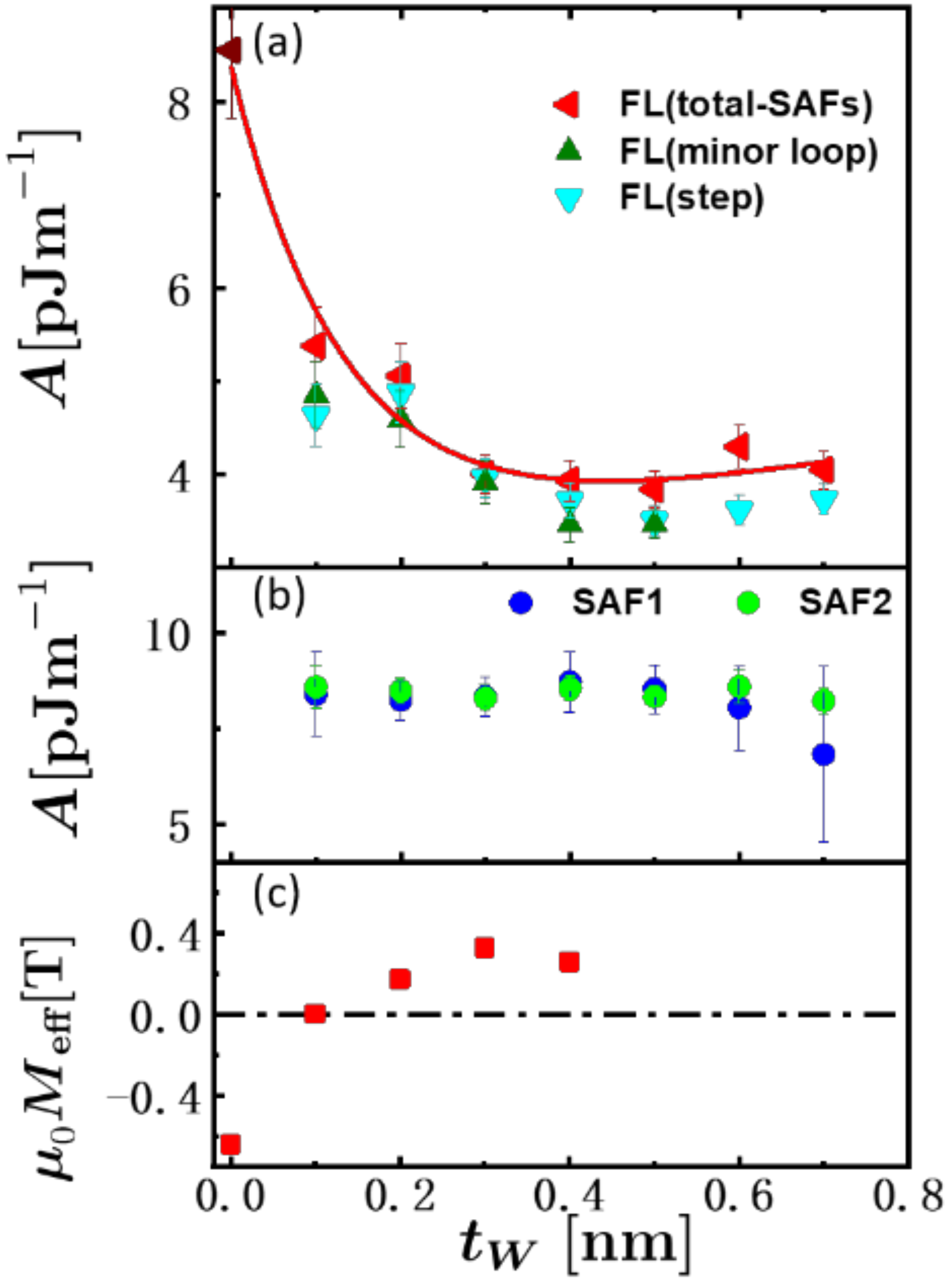
  -Non-magnetic layers are inserted to:
  - Increase the perpendicular magnetic anisotropy (i.e. add interfaces and interface magnetic anisotropy)
  - Enable increased layer thickness and thus magnetic volume to increase the magnetic stability



- We did experiments to determine the exchange constant and magnetic anisotropy of CoFeB/W/CoFeB composite free layers as a function of the tungsten insertion layer thickness.

Magnetic Anisotropy and Exchange Energy





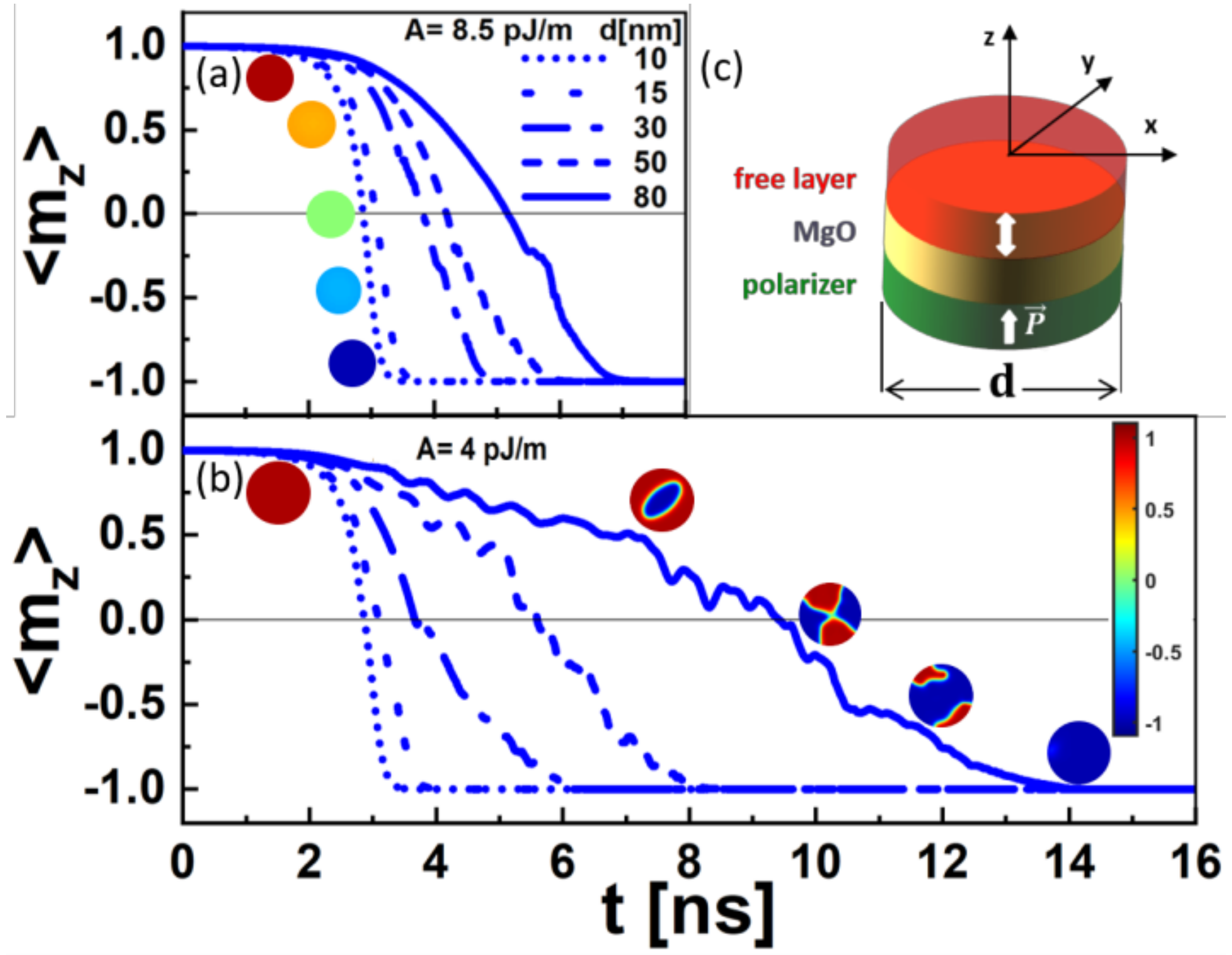
$$K_{\text{eff}} = K_p - \frac{\mu_0 M_s^2}{2}$$

$$M_{\text{eff}} = \frac{2K_{\text{eff}}}{\mu_0 M_s}$$

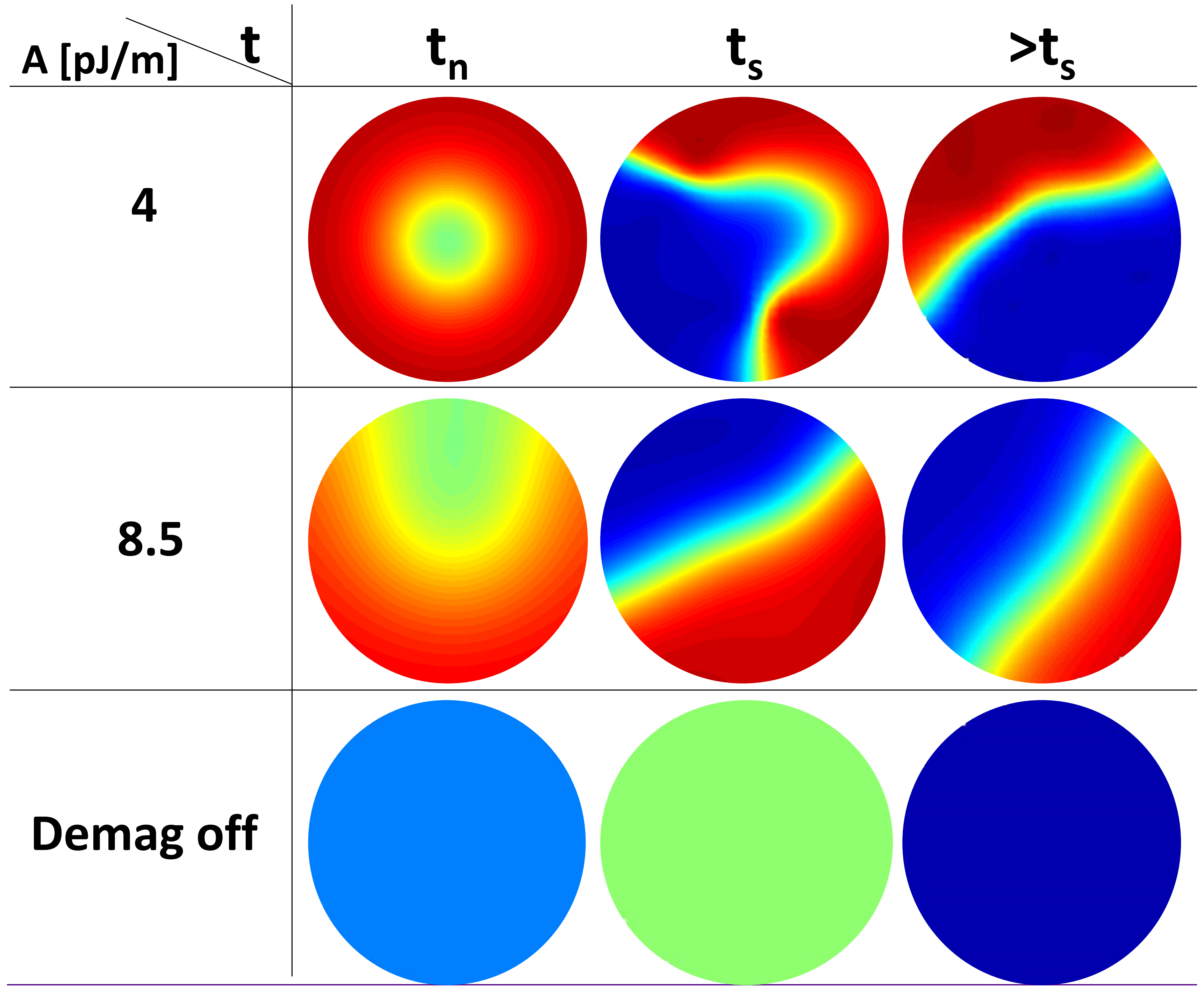
Jamileh Beik Mohammadi *et al.*, "Reduced Exchange Interactions in Magnetic Tunnel Junction Free Layers with Insertion Layers," ACS Appl. Electron. Mater **1**, 2025 (2019)

Micromagnetic Modeling

Magnetization vs time



Switching process



t_n: nucleation time
t_s: switching time, m_z=0

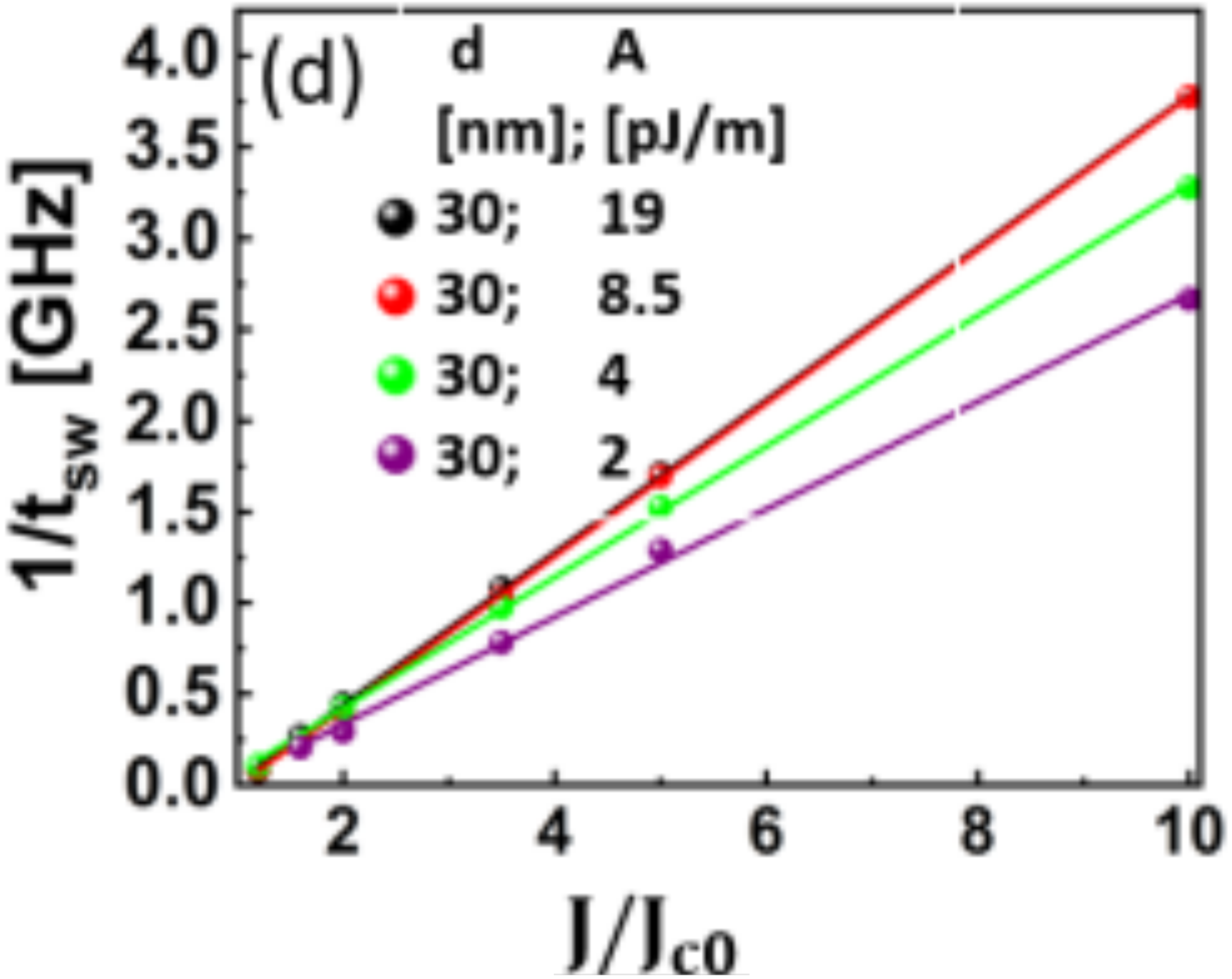
Switching process:

-Reversal in the center of the disk (formation of a reversed droplet)
-Reversed area moves to intersect the boundary (droplet drift instability)
-Domain wall formed that traverses the element
-Reversal by domain wall motion

see also, P. Bouquin *et al.*, APL 2018

Micromagnetic Modeling

Switching speed



t_s: switching time, m_z=0

$$\frac{1}{\tau} = \frac{1}{\tau_0}\left(\frac{I - I_c}{I_c}\right)$$

Switching speed:

-Switching rate is proportional to the current, independent of exchange constant

-Switching rate at fixed overdrive increases with increasing exchange constant

J. B. Mohammadi and AD. D. Kent, “Spin-torque switching mechanisms of perpendicular magnetic tunnel junctions nanopillars,” arXiv:2003.13875 (2020).

see also, P. Bouquin *et al.*, APL 2018

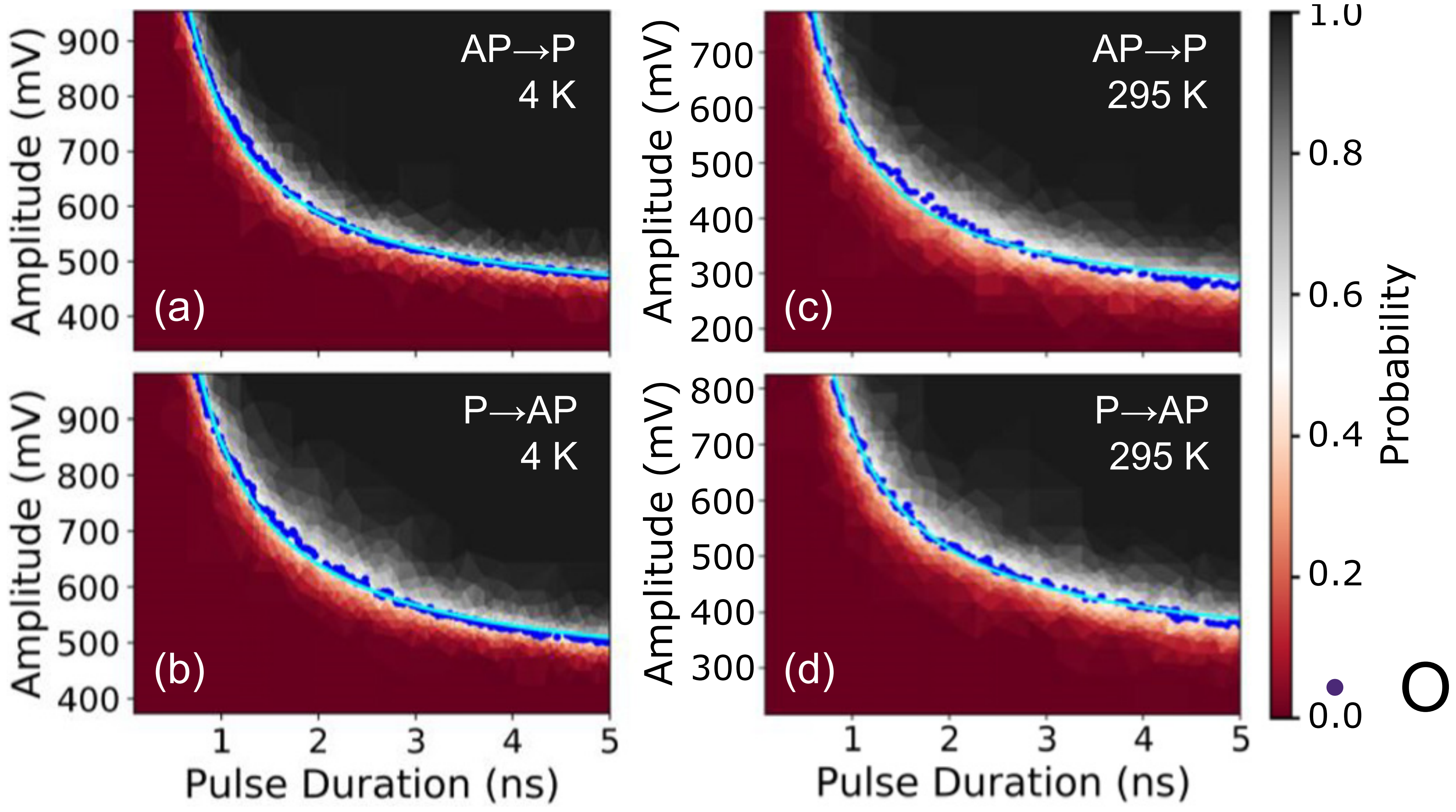
Physics and Applications of Spin-Transfer Torques

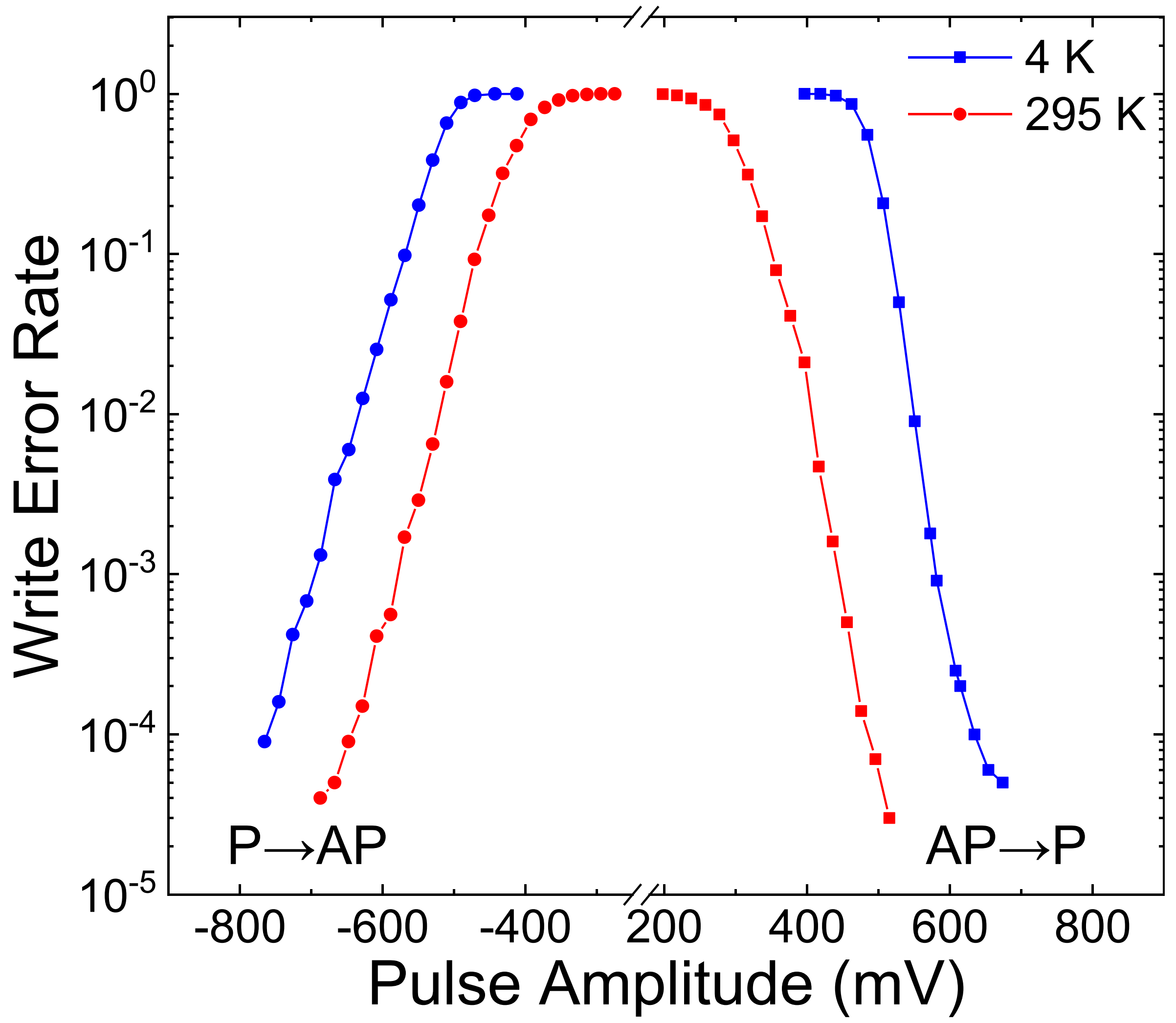
Outline

- Magnetic tunnel junctions and spin-transfer torques
- Applications
- Switching of magnetization, materials and device optimization
- **Cryogenic applications**

Cryogenic Memory

Switching speed





Switching energy

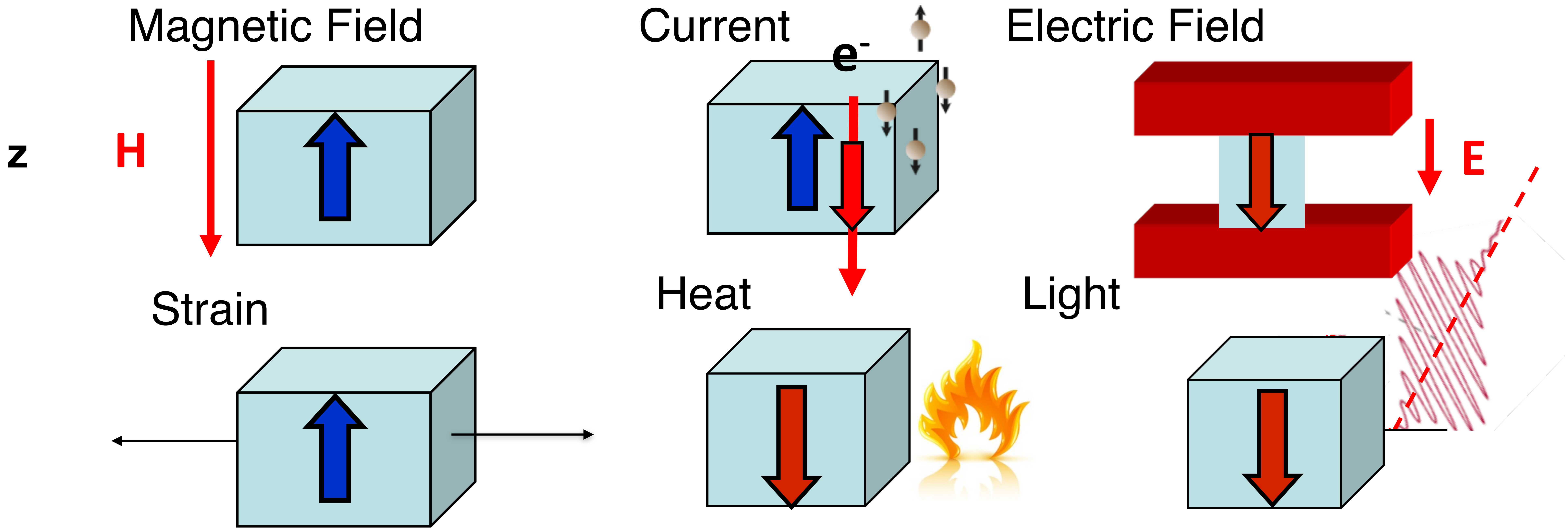
T (K)	V_c (mV)		τ_0 (ns)		*E* (fJ)	
	AP→P	P→AP	AP→P	P→AP	**AP→P**	**P→AP**
4	399	421	0.94	1.03	**103**	**286**
75	393	416	0.94	1.05	**98**	**283**
150	381	403	0.96	1.1	**94**	**287**
295	225	305	1.48	1.38	**51**	**195**

- Optimal write energy increases with decreasing temperature
  - ➢ Thermal energy reduces device switching energy
- Comparison to already studied cryogenic memory devices:
  - Orthogonal spin-transfer device: ~235 fJ
  - Spin-valve device with Py FL: ≤ 230 fJ
  - Three-terminal CSHE device: ~5.6 pJ

➡ Surprisingly low write energies due to very low switching currents of 69 (AP→P) and 165 μA (P→AP) compared to e.g. 0.9 mA for three-terminal device!

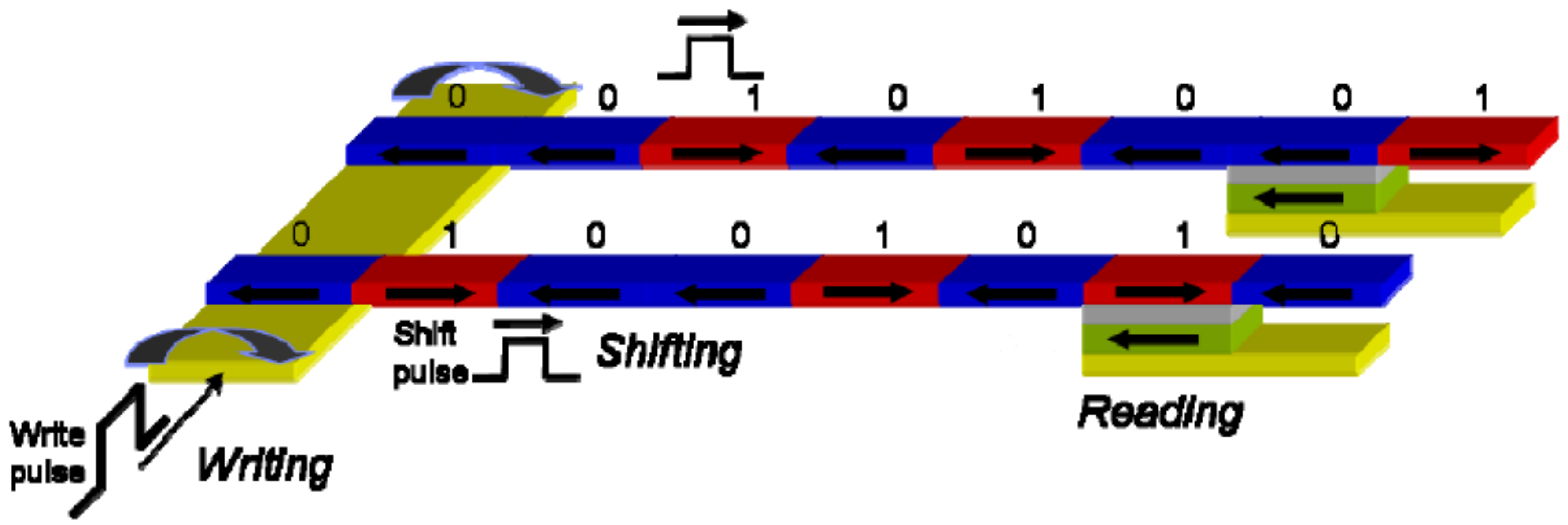
Laura Rehm *et al.*, APL **115**, 182404 (2019)

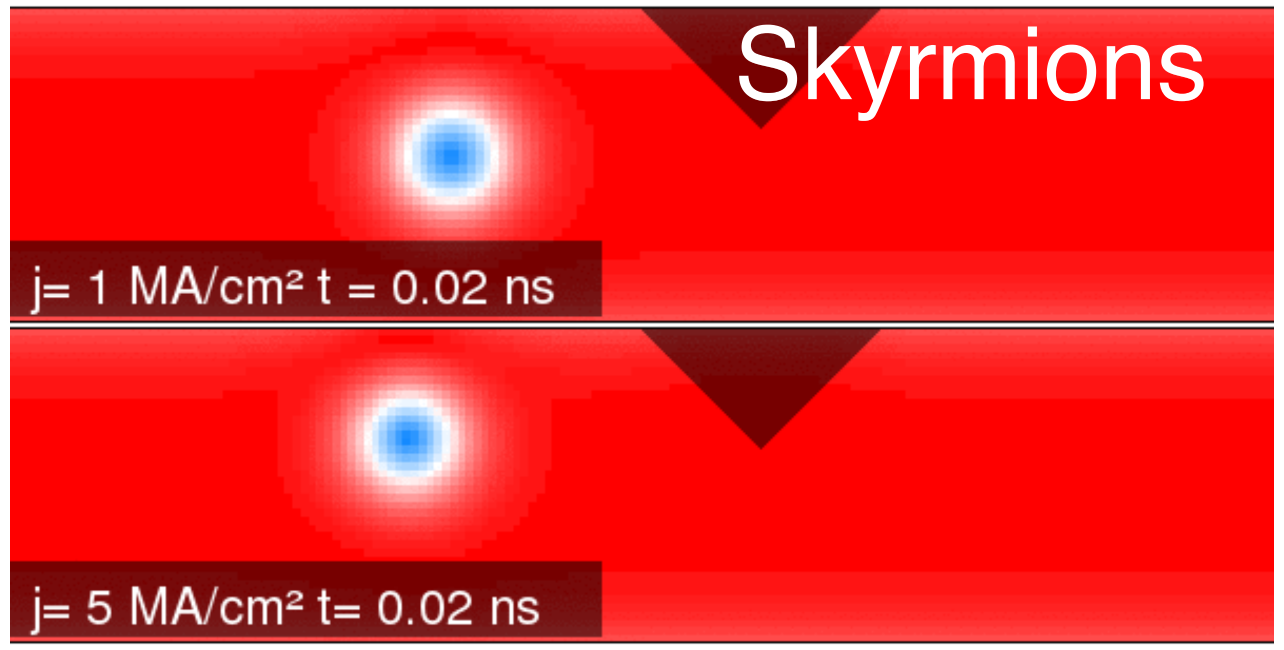
New Magnetic Technologies



Idea of moving information without moving the magnetic material!

Domain walls



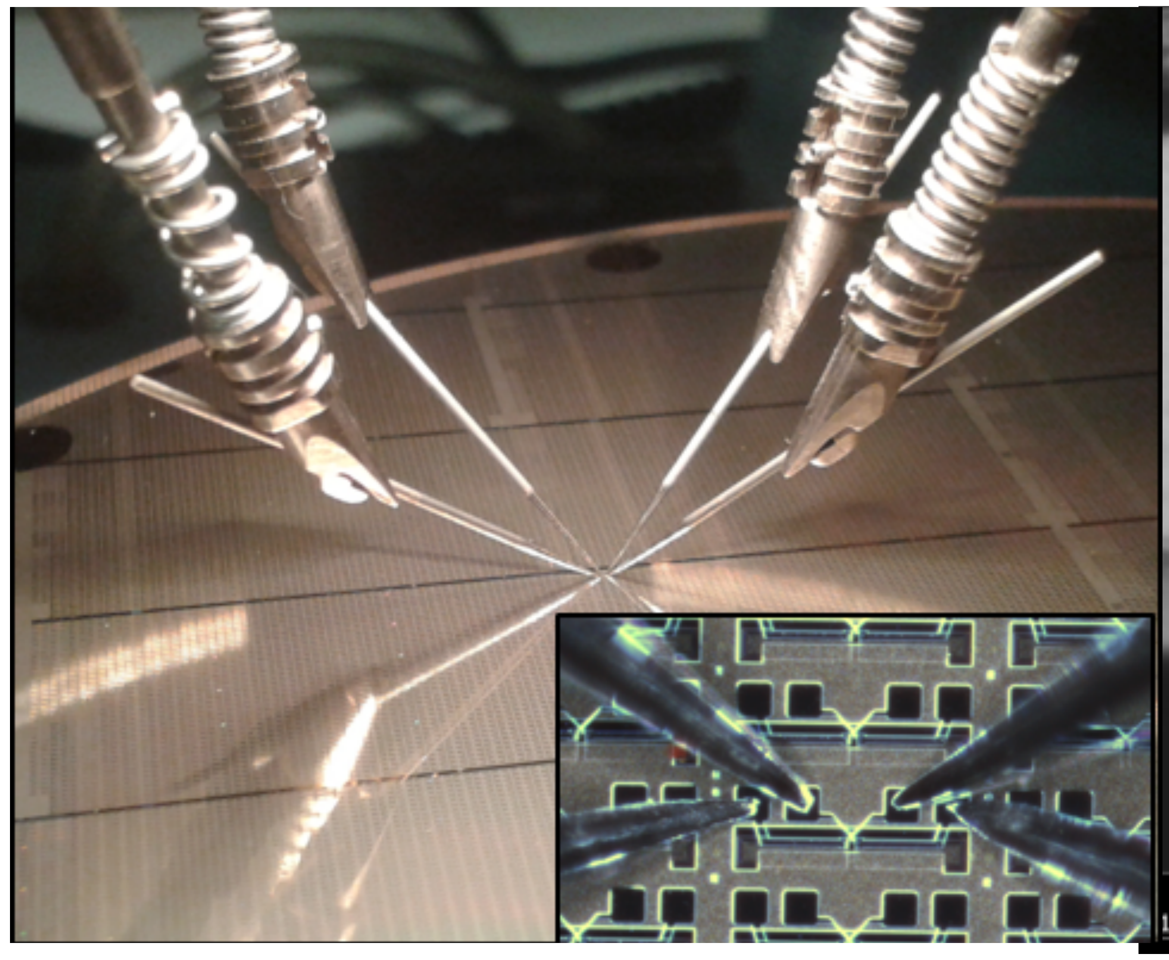


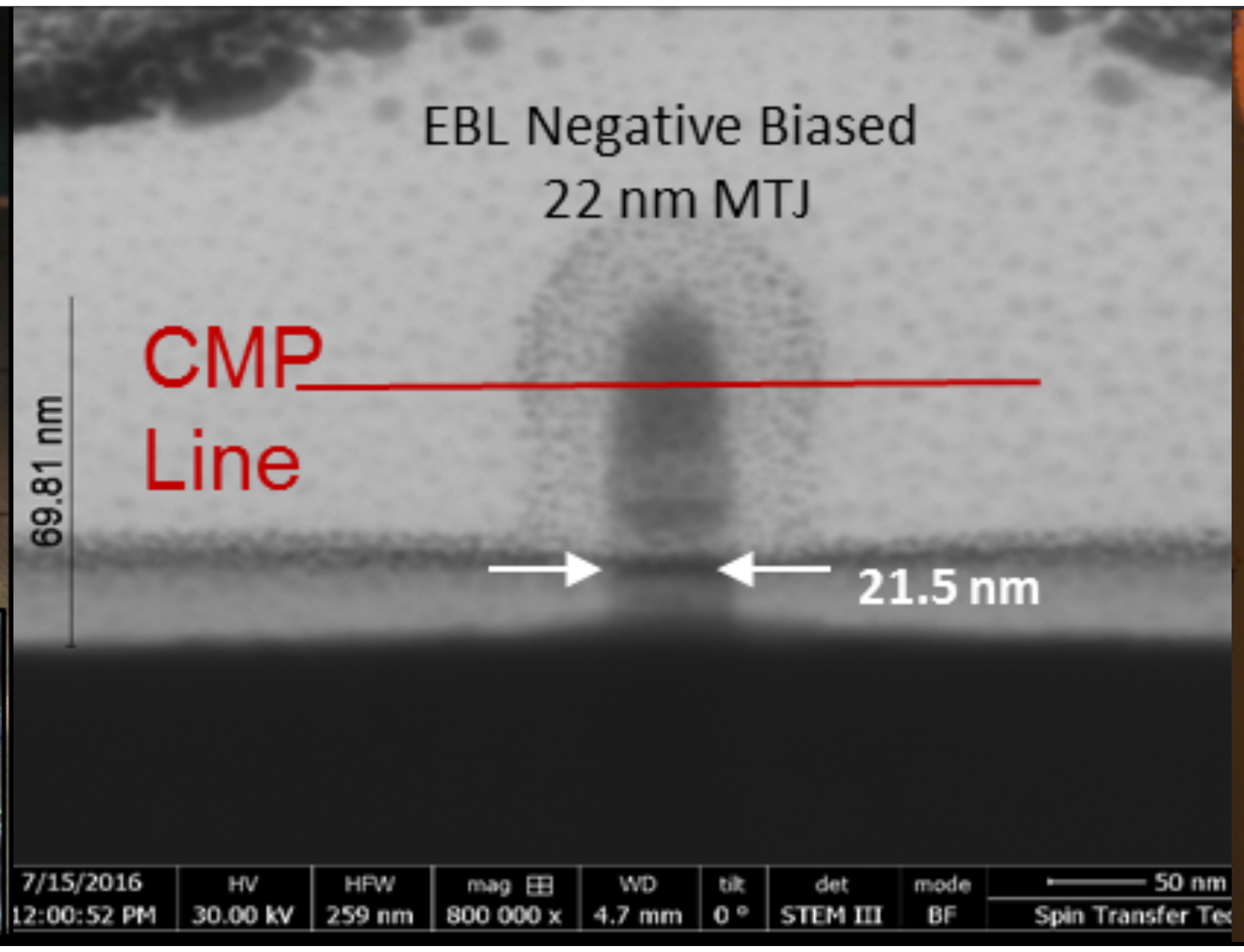
S.S.P. Parkin, Racetrack Memory 2008

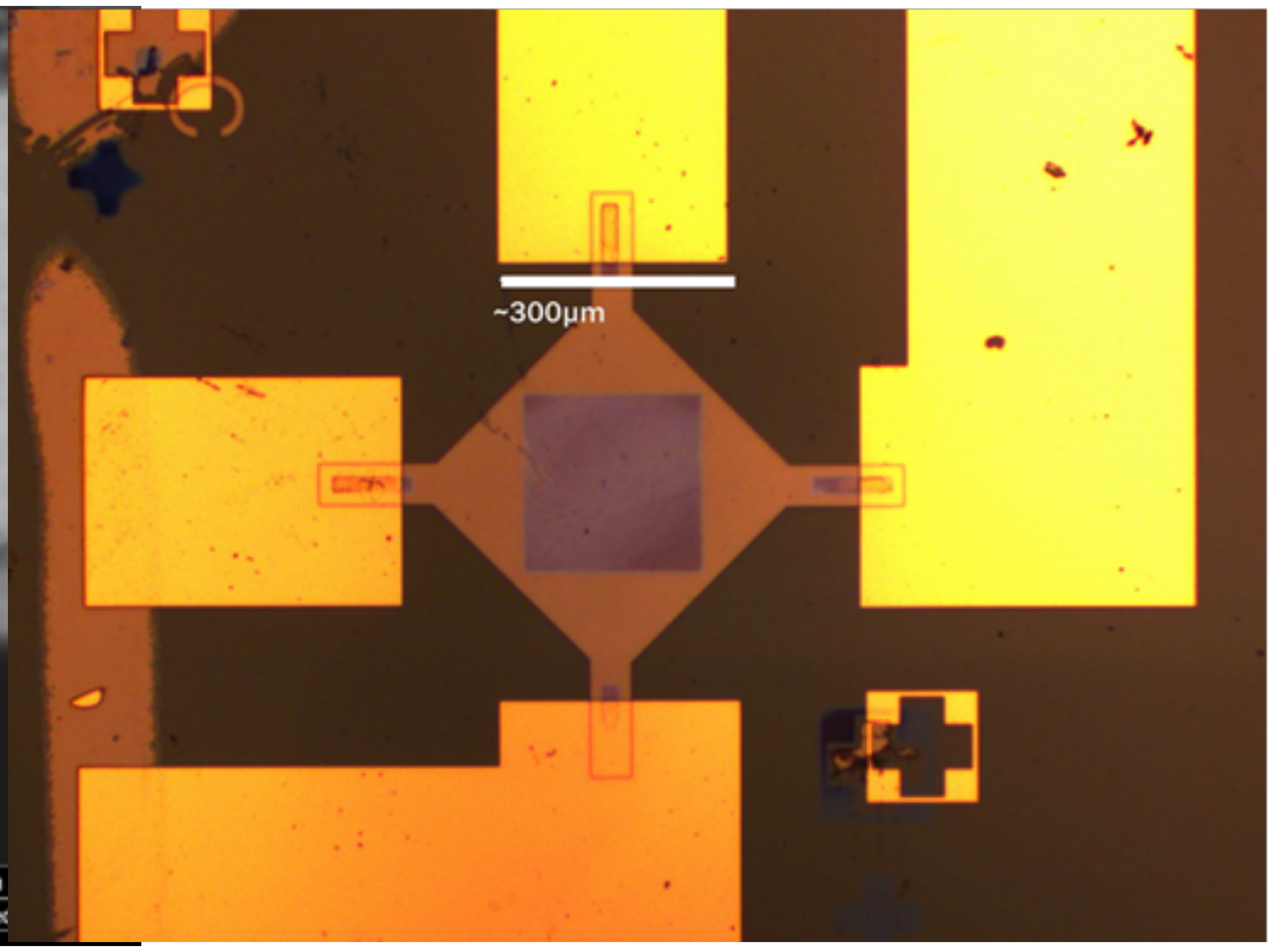
A. Fert, V. Cros, J. Sampaio, *Nature Nano*. **8**, 152 (2013)
J Sampaio *et al.*, Nature Nano. 8, 839 (2013)

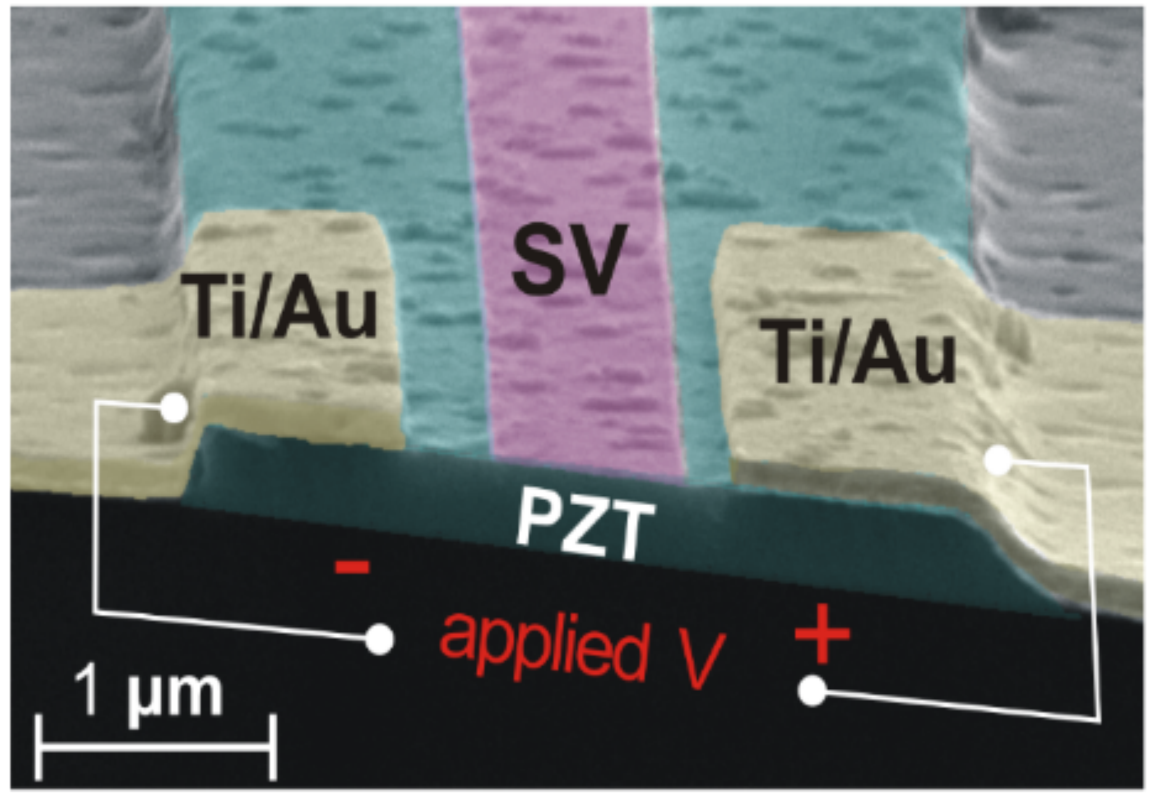
New Magnetic Nanotechnologies

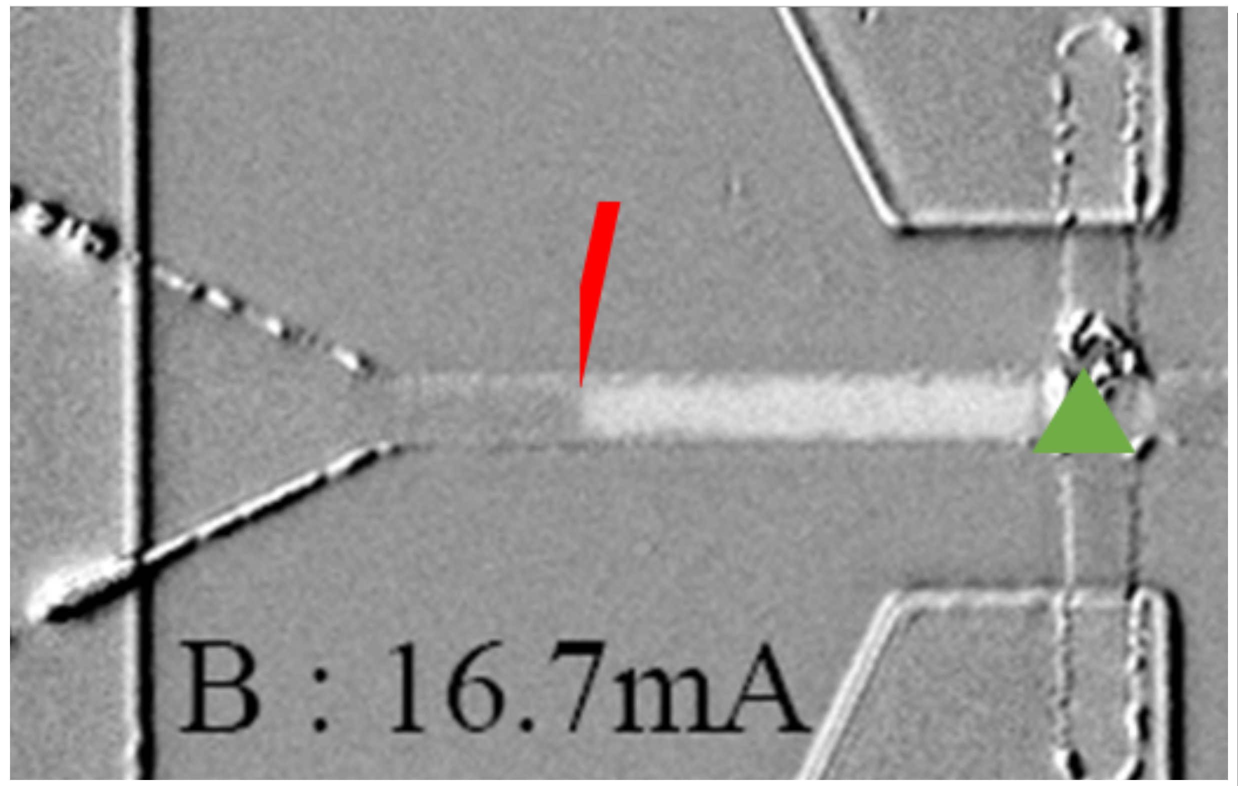
Nanoelectronics, from new phenomena to low power electronics

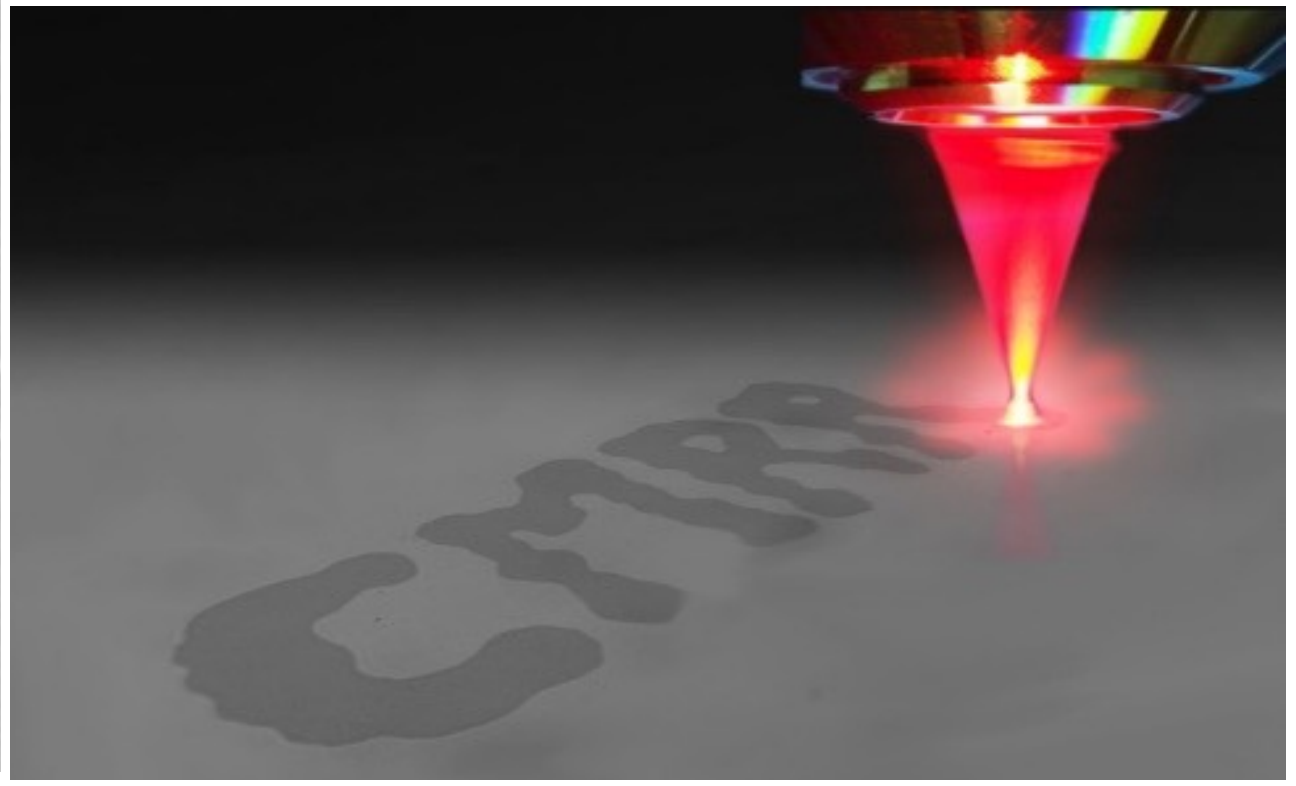












International Associated Laboratory (LIA)

UCSD

UNIVERSITÉ DE LORRAINE

université PARIS-SACLAY

NYU

Summary

- Magnetic tunnel junction and spin transfer torques
- Applications
- Switching of magnetization, materials and device optimization
- Cryogenic applications

Acknowledgments

NYU Team: Dirk Backes*, **Gabriel Chaves***, Eason Chen, Ege Cogulu, Daniel Gopman*, **Christian Hahn***, Jinting Hang*, Yu-Ming Hung*, Marion Lavanant*, Ferran Macia*, **Jamileh Beik Mohammadi**, Daniele Pinna*, **Laura Rehm**, Debangsu Roy, Sohrab Sani*, Volker Sluka, **Georg Wolf***, Li Ye* & Junwen Xu (*=group alumni)

Collaborators

-Colorado State University: Houchen Chan, Jjinjun Ding, Tao Liu & Mingzhong Wu

-Advanced Light Source, Berkeley: Hendrik Ohldag

-IBM T. J. Watson Research Center: Jonathan Z. Sun

-NYU: Gabriel Chaves and Dan Stein

-University of Barcelona and ICMAB-CSIC: Nahuel Statuto & Ferran Macia

-UVA: Joseph Poon and Avik Ghosh

-BBN Raytheon: Tom Ohki, Colm Ryan & Graham Rolands

-Spin Memory: Georg Wolf, Bartek Kardasz, Steve Watts & Mustafa Pinarbasi

-University of Buffalo: Igor Zutic

-Wayne State: Alex Matos Abiague

-University of Lorraine: Stephane Mangin & Sebastien Petit-Watelot

-U. Paris Saclay, C2N: Dafine Ravelosona

-UCSD: Eric Fullerton

-WD-HGST: Jordan Katine