A New Spin on Magnetism with Applications in Information Processing

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NYU Abu Dhabi: Center for Quantum and Topological Systems: Colloquium, November 21, 2022

A New Spin on Magnetism with Applications in Information Processing

Outline

- Spintronics and spin-transfer torques
- Switching magnetization in magnetic tunnel junction nanopillars
- Magnetic skyrmions
- Center for Quantum Phenomena NYU NY

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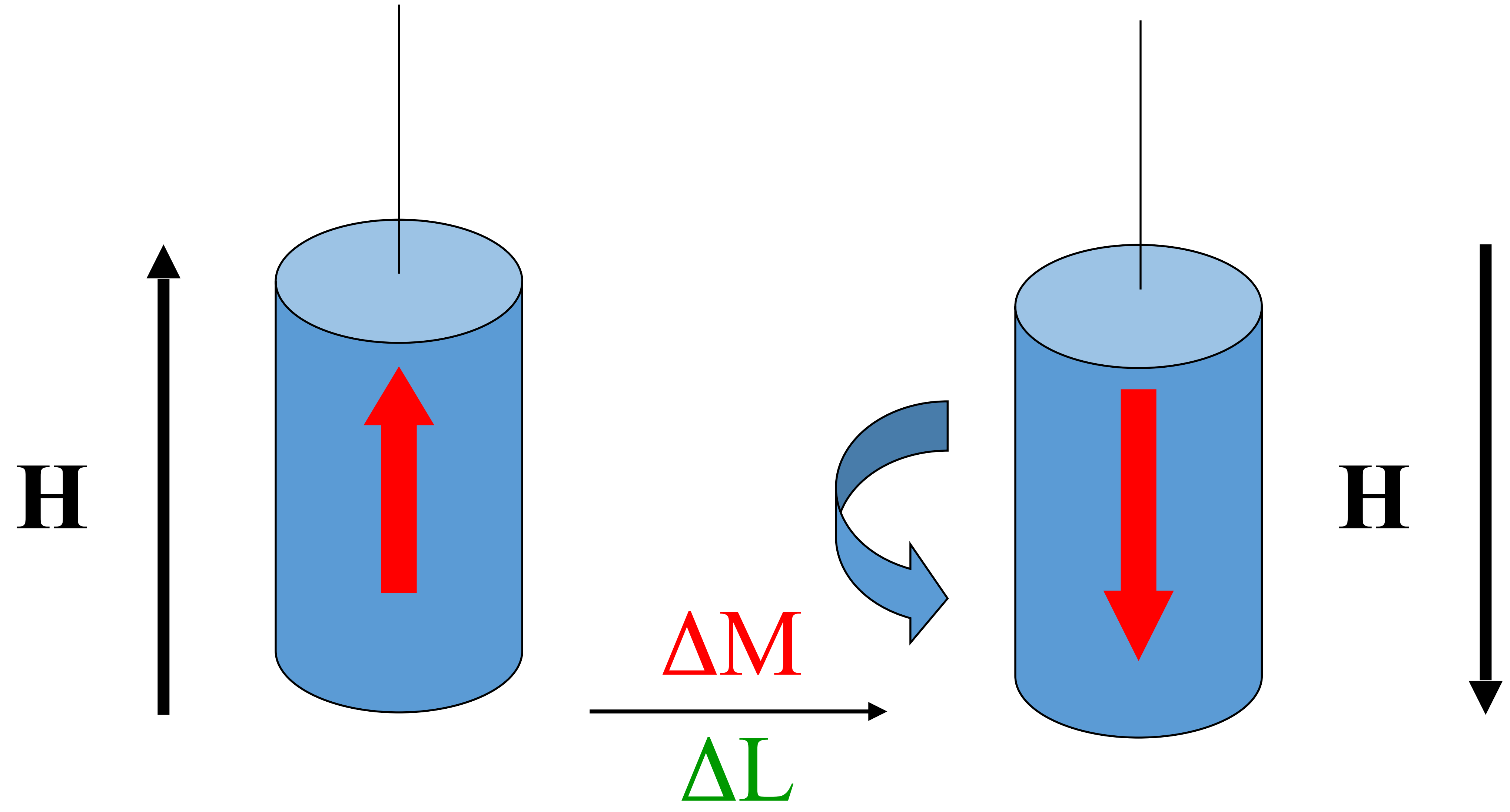
Einstein-de Haas Effect



$$\boxed{\Gamma = \frac{dL}{dt}} \Rightarrow \boxed{\text{Rotation}}$$

$$M = \gamma L \qquad \gamma = \frac{ge}{2m} = \frac{g\mu_B}{\hbar}$$

[redacted]

A. Einstein, W. J. de Haas, *Experimenteller Nachweis der Ampereschen Molekularstörme*, Deutsche Physikalische Gesellschaft, Verhandlungen **17**, pp. 152-170 (1915).

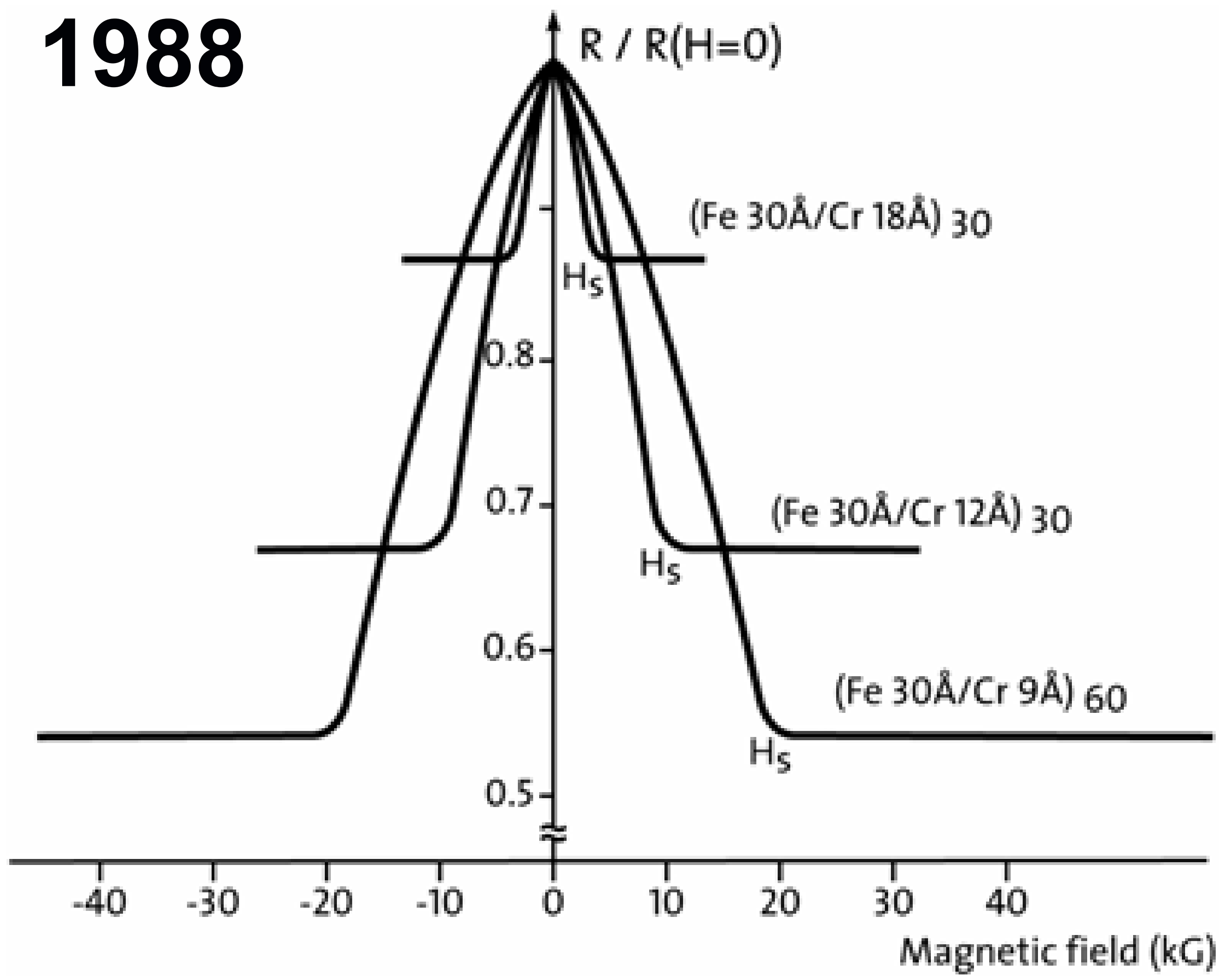
Proof of the existence of the Ampere molecular field

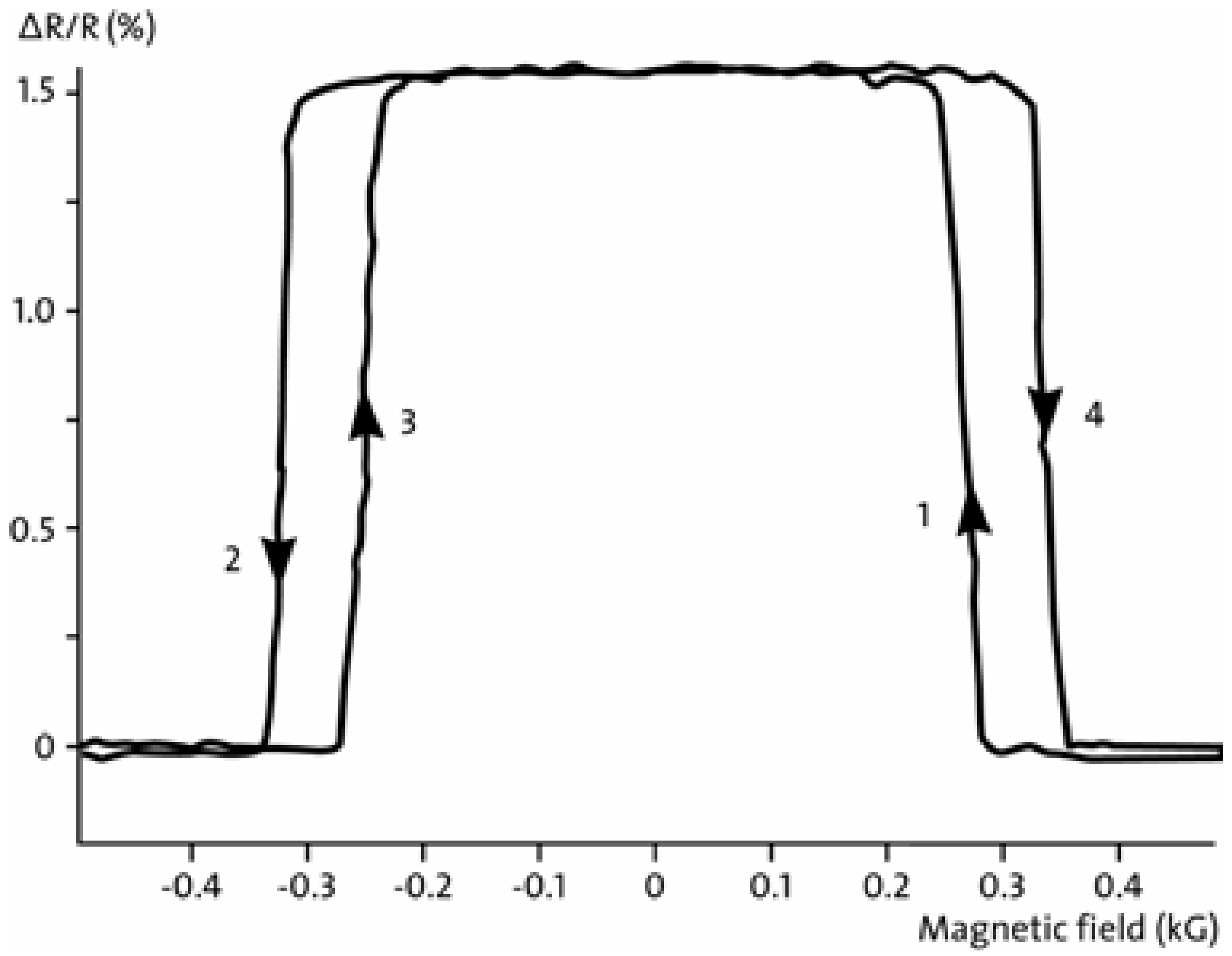
Giant Magnetoresistance (GMR)

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

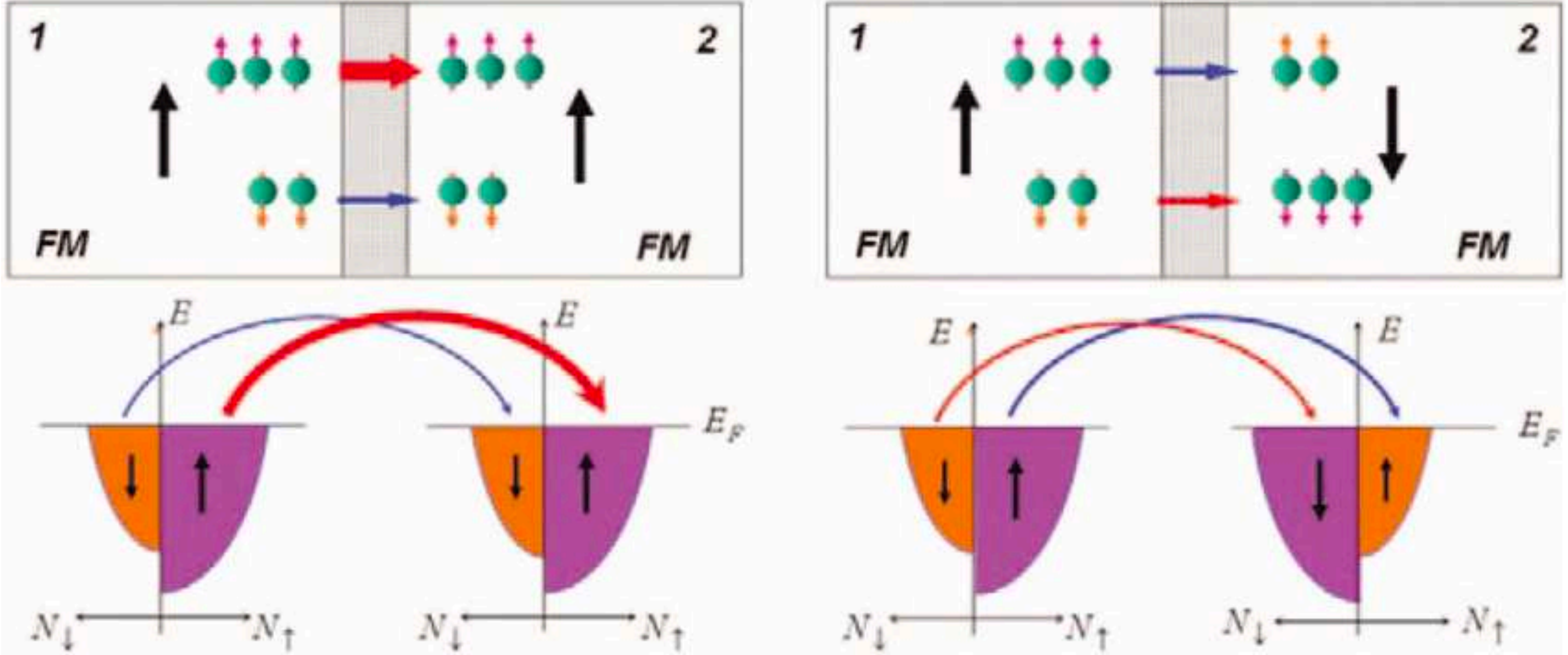




→ ‘Spintronics’= **Spin**+**Tr**ansport+Electr**onics**: control of current using the spin of electrons

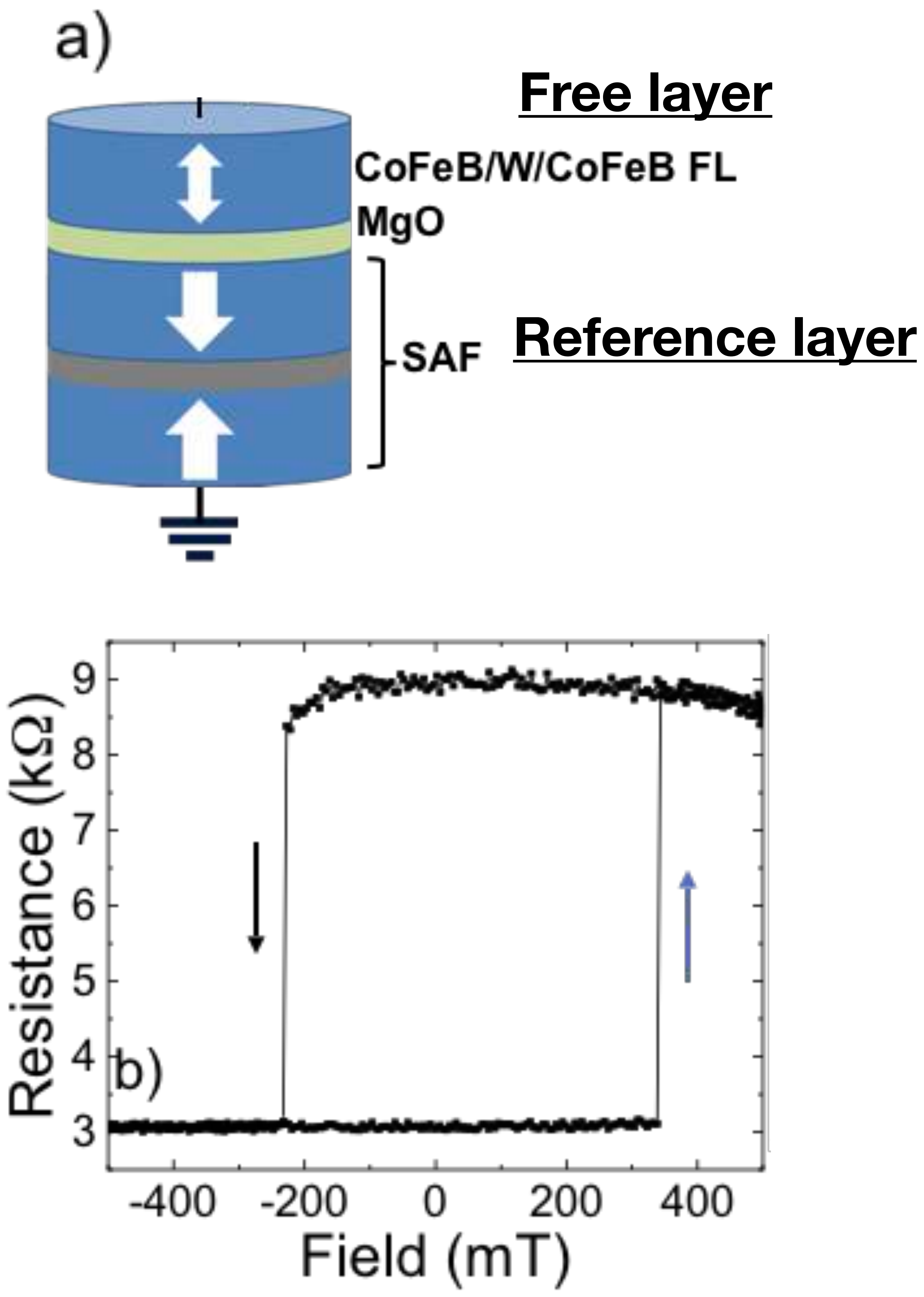
Magnetic Tunnel Junction

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)

Prediction of Spin-Transfer Torques

2013 APS Oliver E. Buckley Prize

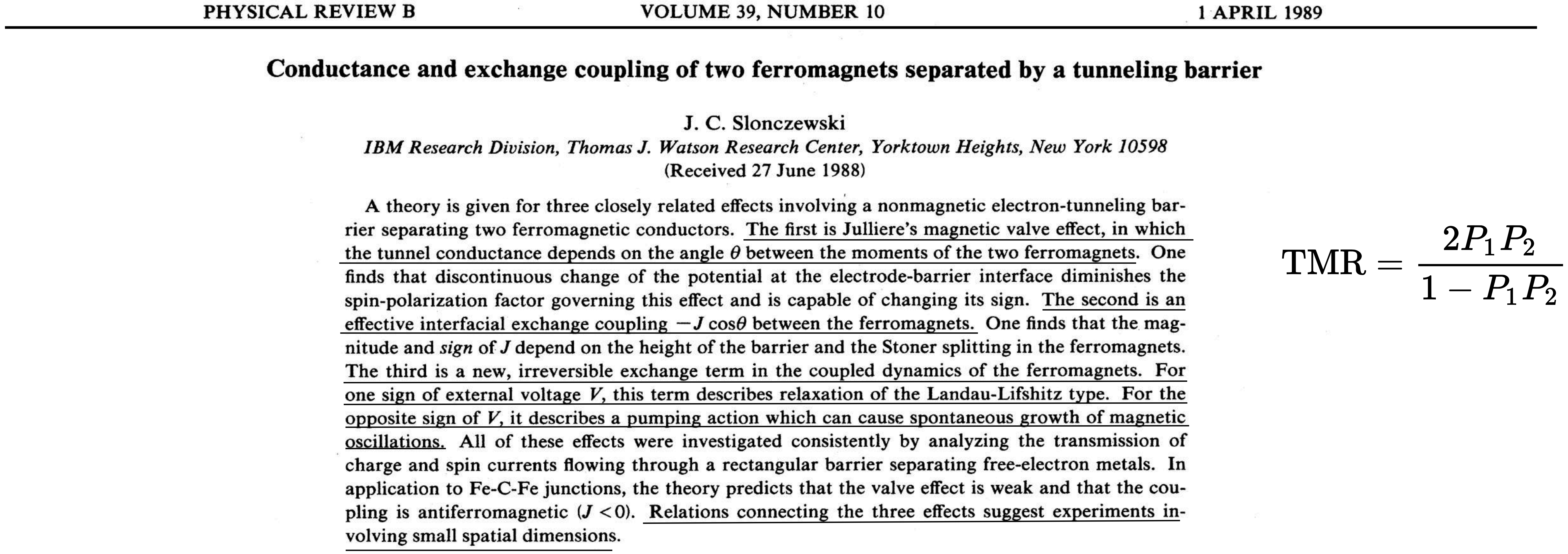
John Slonczewski

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)

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

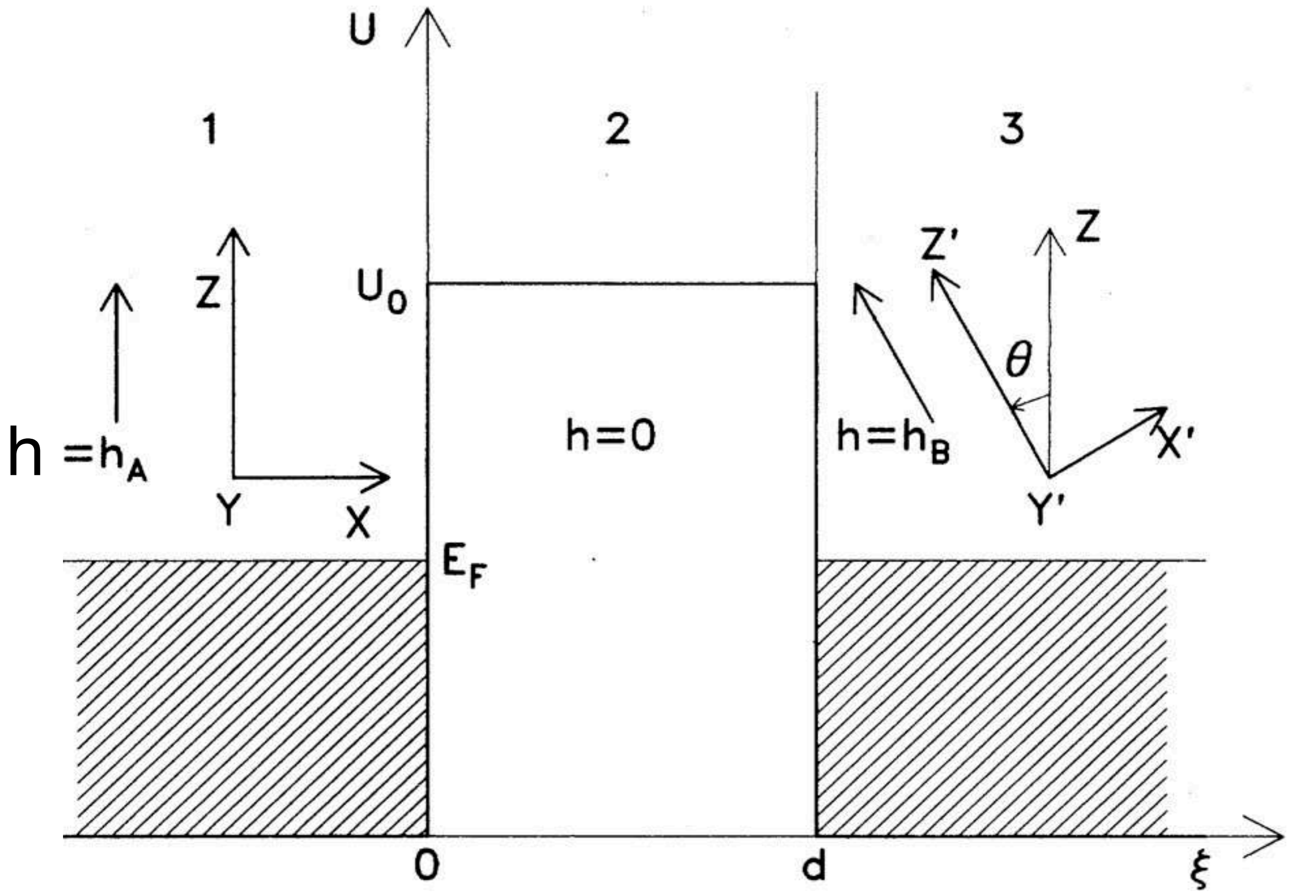
J. C. Slonczewski
IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, New York 10598

(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



In magnetic metallic multilayers

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

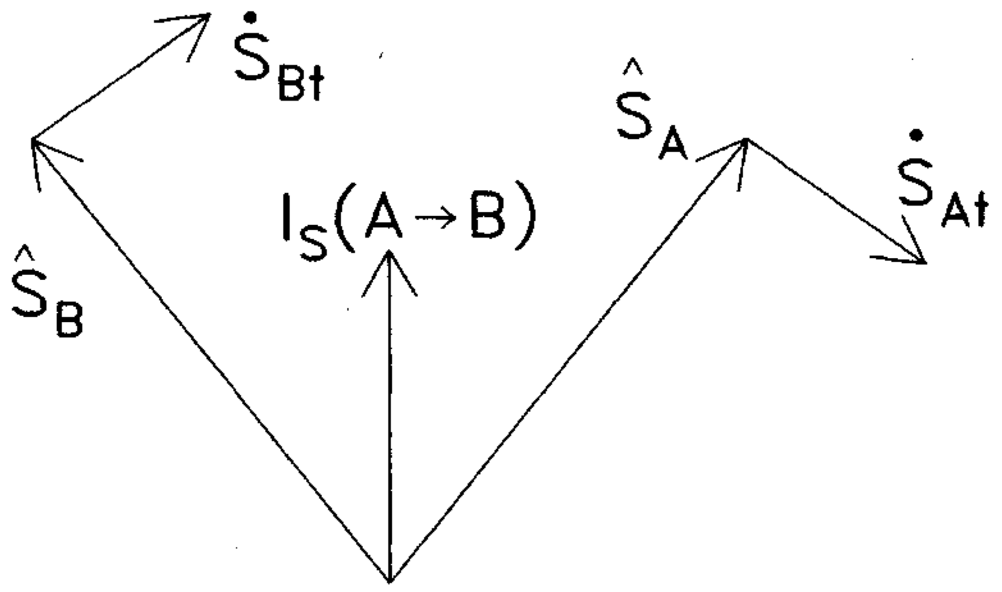
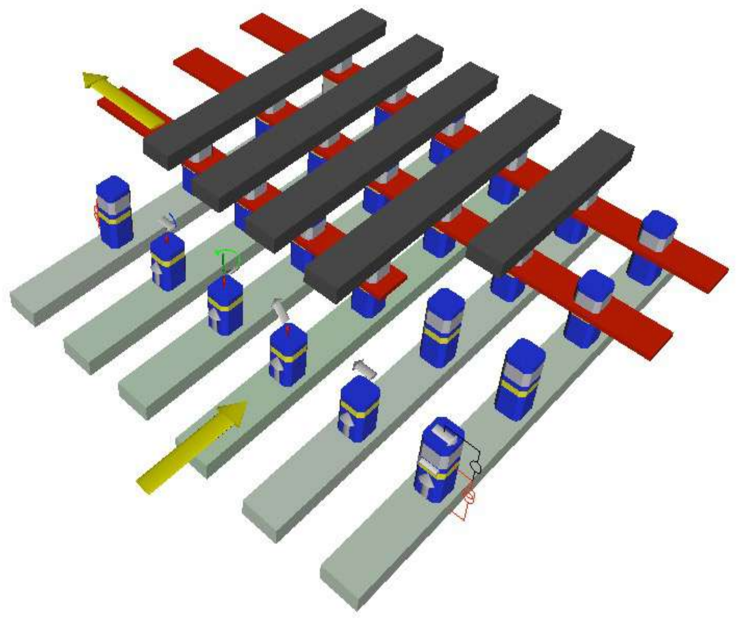


FIG. 6. Scheme of spin-vector dynamics due to the transverse terms of dissipative exchange coupling induced by an external voltage across the barrier.

Applications: New types of MRAM

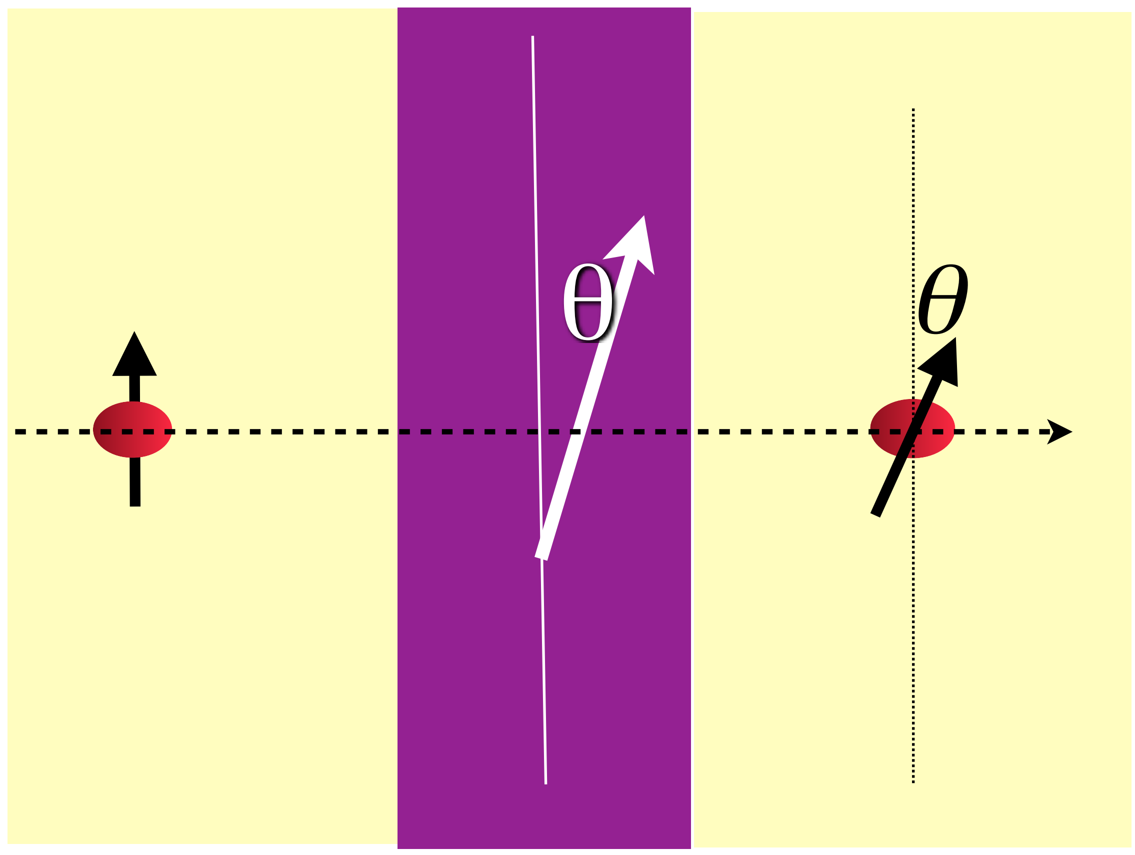


Applications: Magnetic Random Access Memory, STT-MRAM

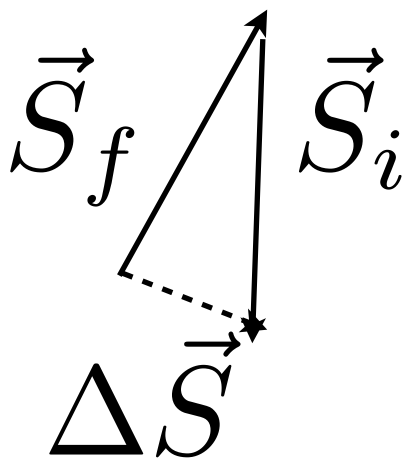
Nature Nanotechnology, March 2015
Spin-transfer-torque memory

Basic Physics of Spin Transfer

Based on conservation of angular momentum



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



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

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

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

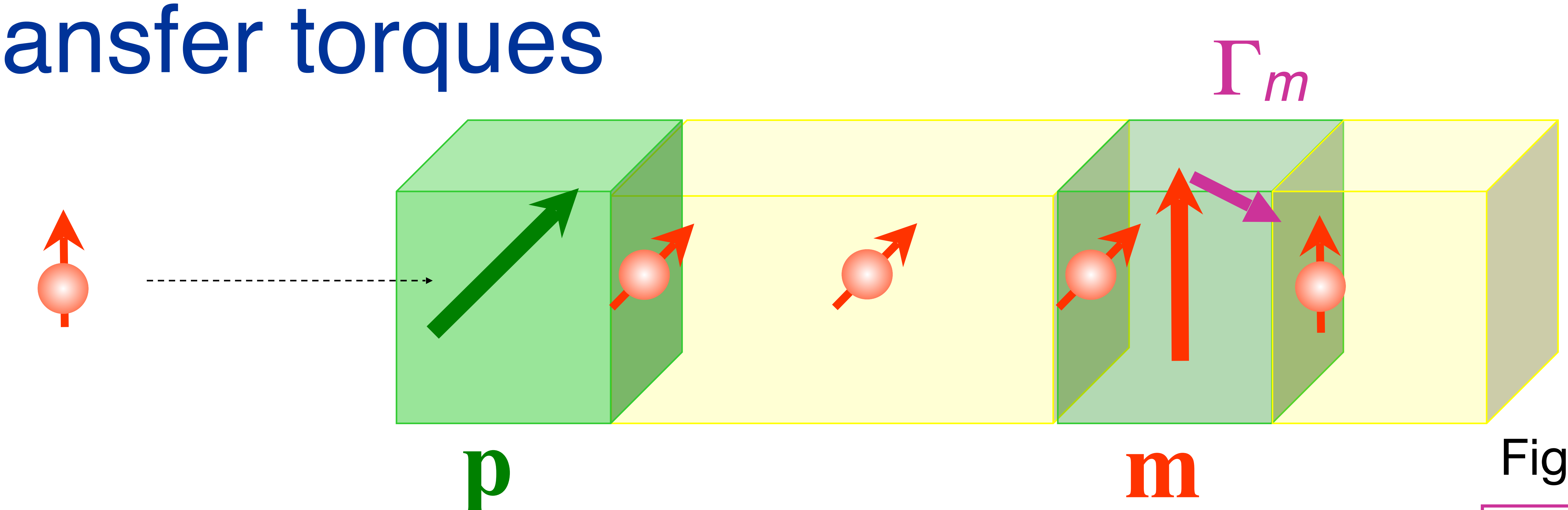


Figure courtesy of Stephane Mangin

Angular momentum conservation
→spin transfer torques

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

- 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

All electrical (no mechanical parts) ⇒fast magnetic memory device

Threshold Current for Magnetic Excitations

Switching

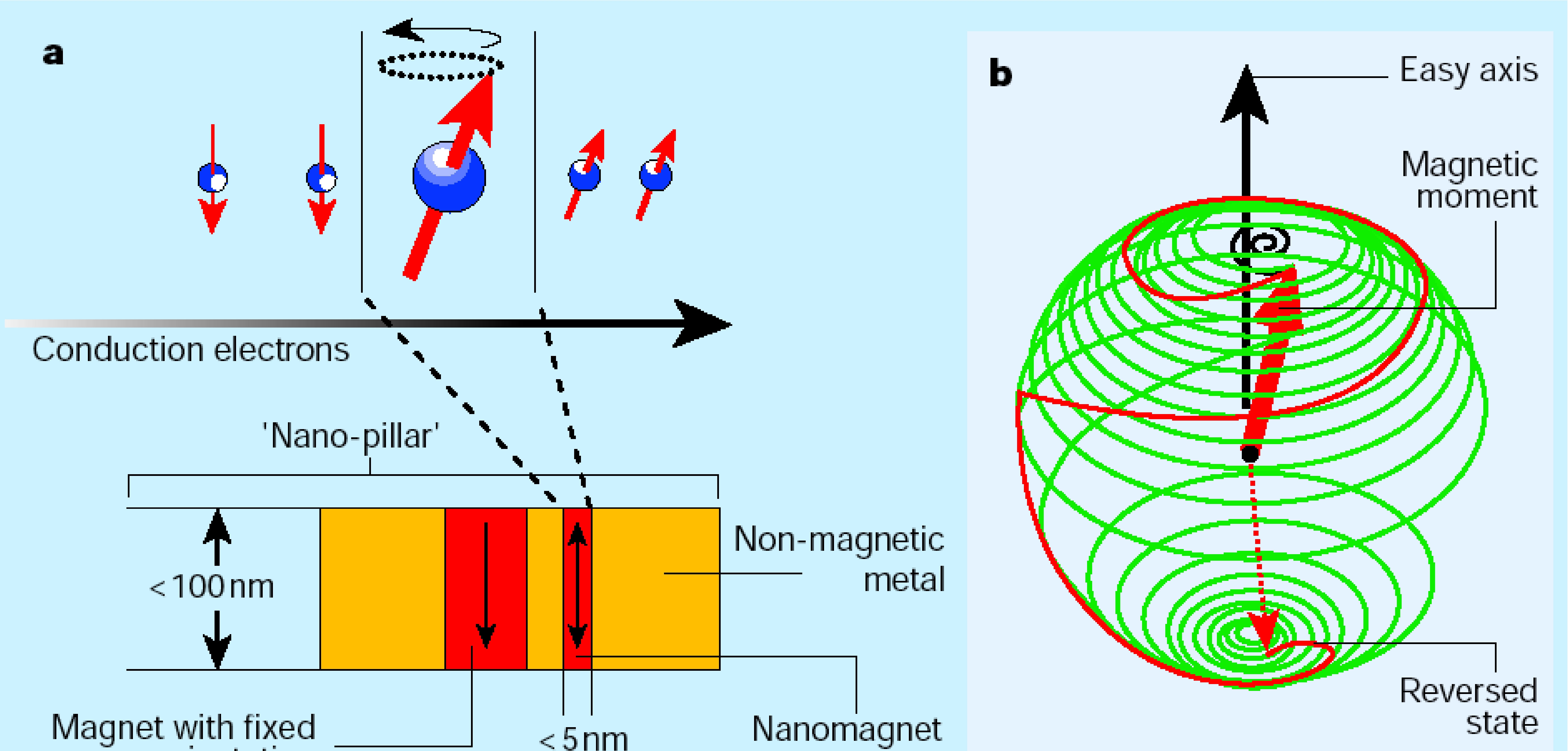
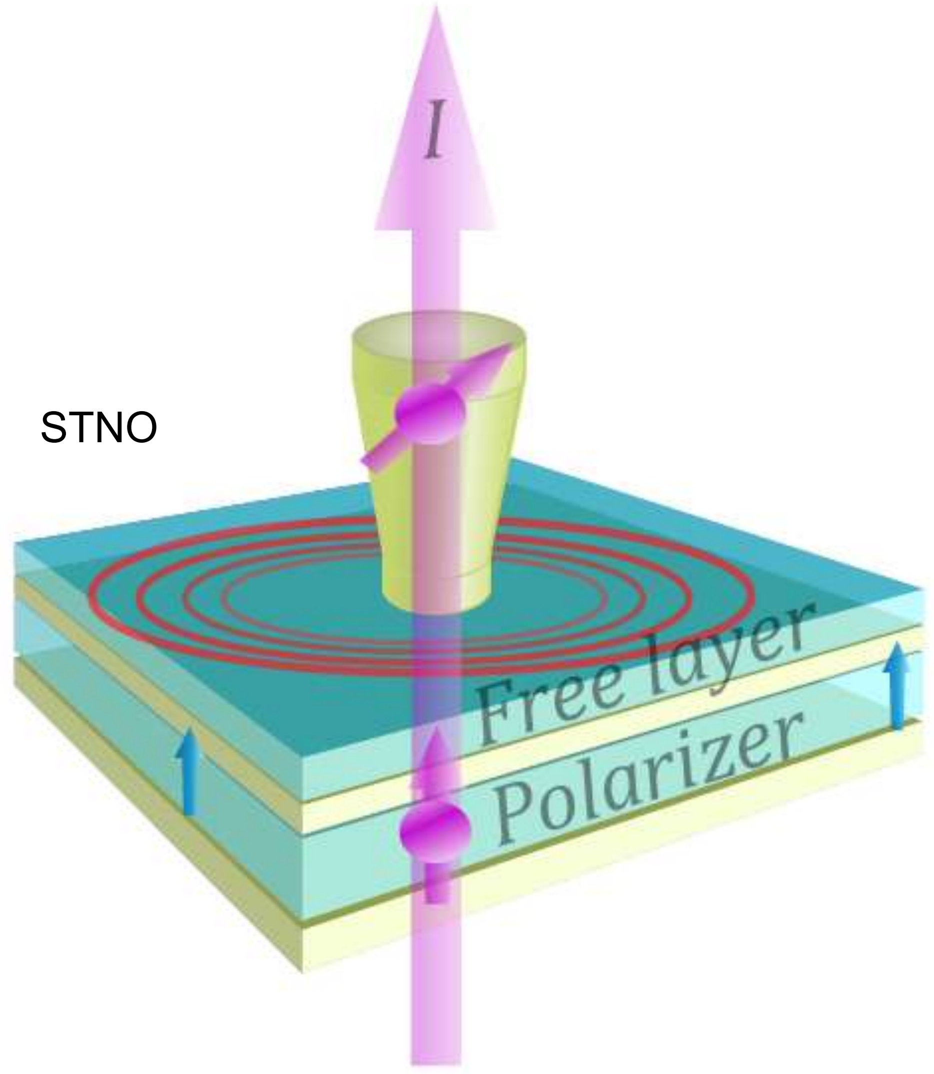


Figure courtesy of J. Z. Sun

Spin-wave excitations

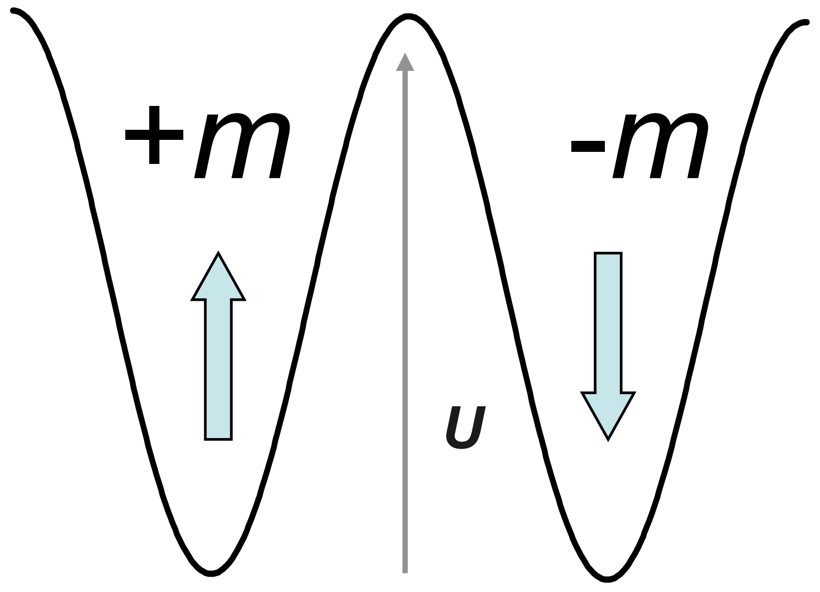


Spin-current amplifies the motion for currents greater than a critical value:

"anti-damping switching"

$$I_{c0} = \frac{2e}{\hbar}\frac{\alpha}{P}\mu_0 M_s H_k V = \frac{4e}{\hbar}\frac{\alpha}{P}U$$

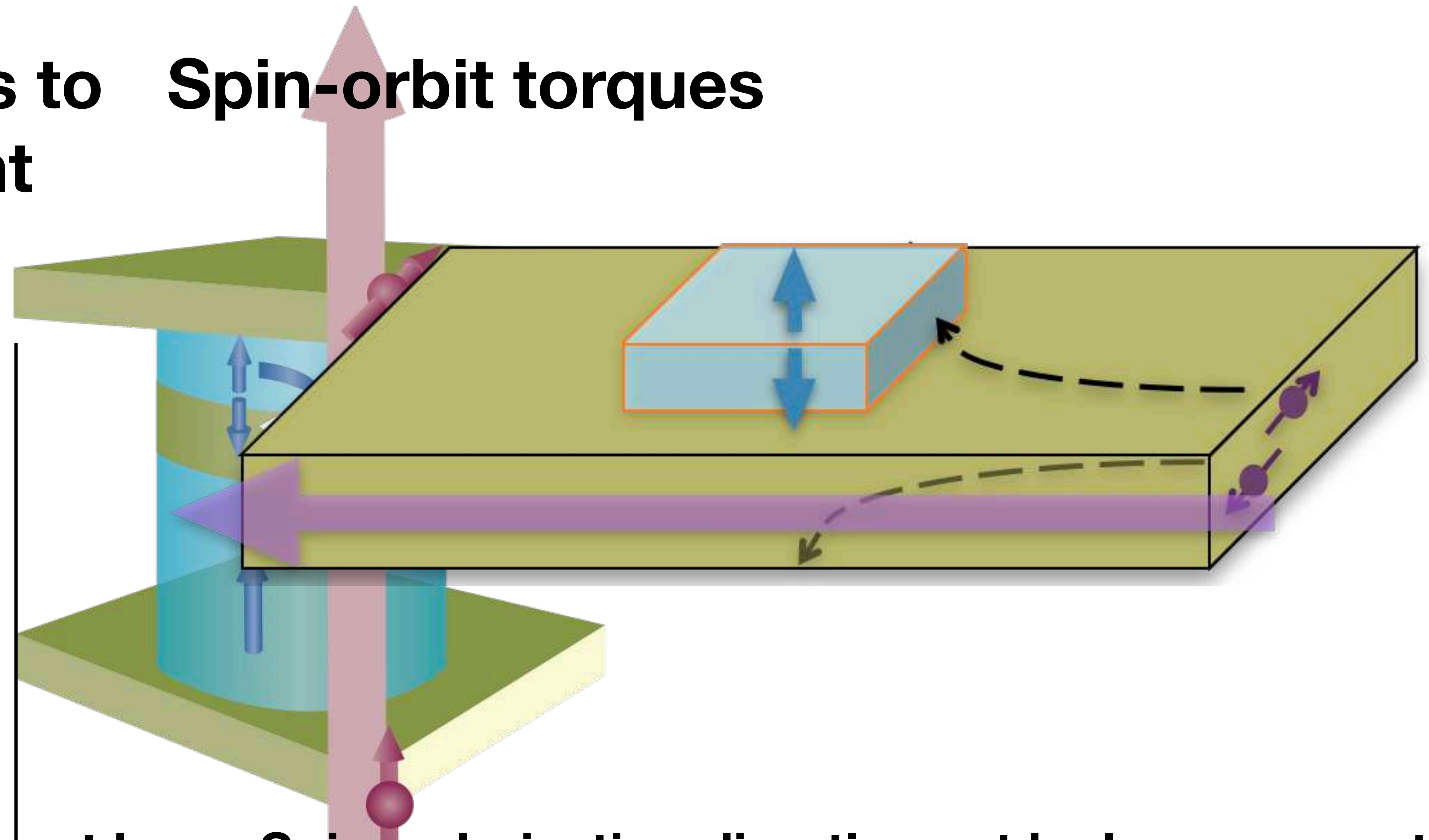
$$P = 1,\ \alpha = 0.01,\ U = 60kT \rightarrow I_{c0} = 15\ \mu\mathrm{A}$$



Charge Current to Spin Current Conversion

Ferromagnetic layers to polarize the current

Spin-orbit torques



Spin-polarization direction set by layer magnetization directions

Spin-polarization direction set by layer geometry and current flow direction

Spin torque foundational theory papers:

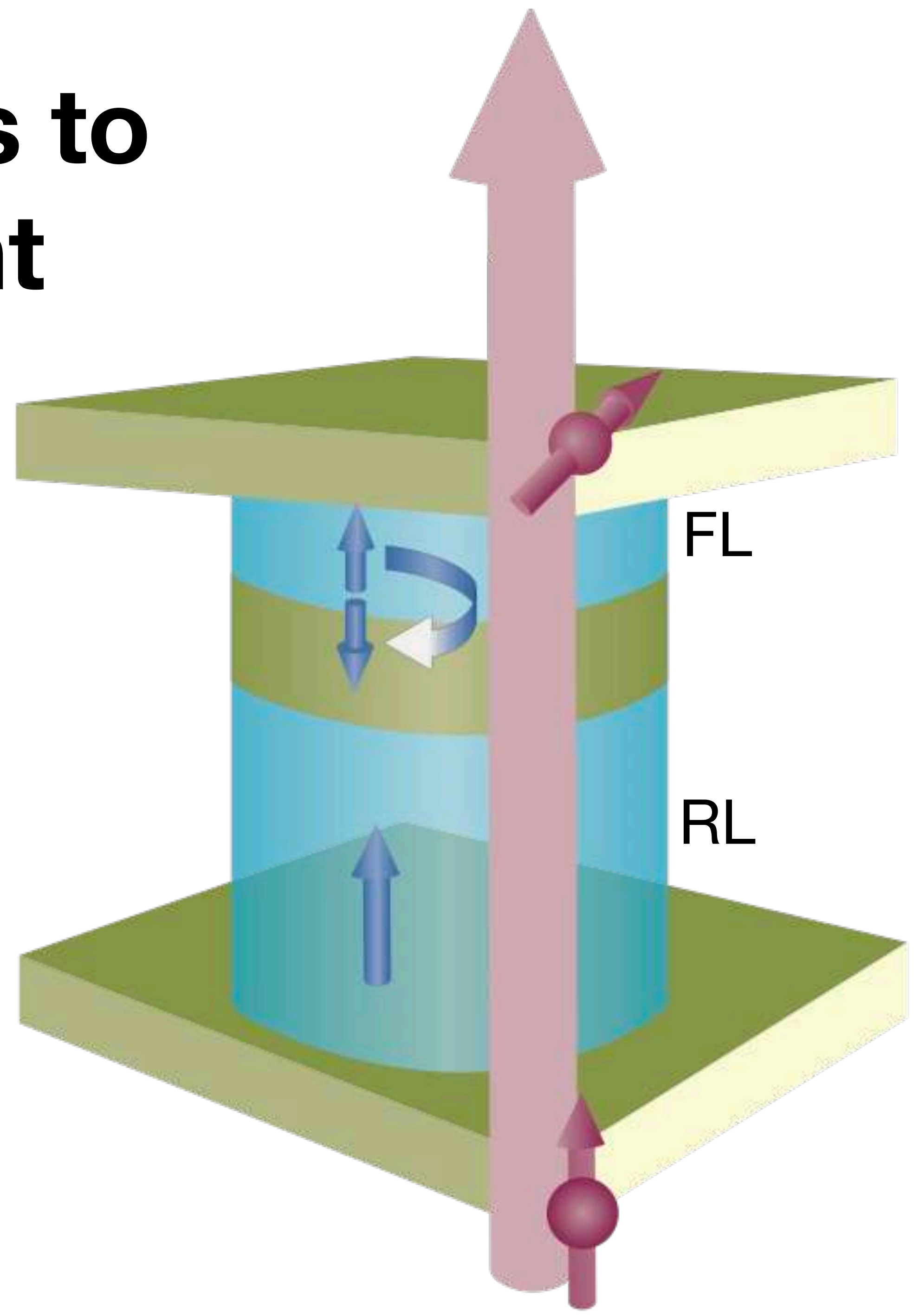
J. C. Slonczewski, Phys. Rev. B. **39**, 6996 (1989)
J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996)
L. Berger, Phys. Rev. B **54**, 9353 (1996)

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

Review articles: J. Sinova *et al.*, Spin Hall Effects, RMP **87**, 1213 (2015)
V. Amin *et al*., Interfacial SOT, J. Appl. Phys. **128**, 151101 (2020)
C. Safranski, J. Z. Sun & ADK, Appl. Phys. Lett. **120**, 160502 (2022)

Charge Current to Spin Current Conversion

Ferromagnetic layers to polarize the current



$$\frac{\text{spin-current density}}{\text{charge current density}} \qquad J_s/J_c \simeq P$$

$$I_s/I_c \simeq P$$

spin current is $\hbar J_s/(2e)$

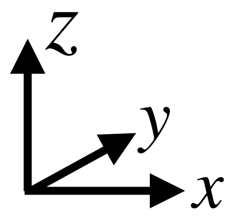
$$\mathbf{Q} \sim \hat{m}_{\mathrm{RL}} \otimes \hat{z}$$

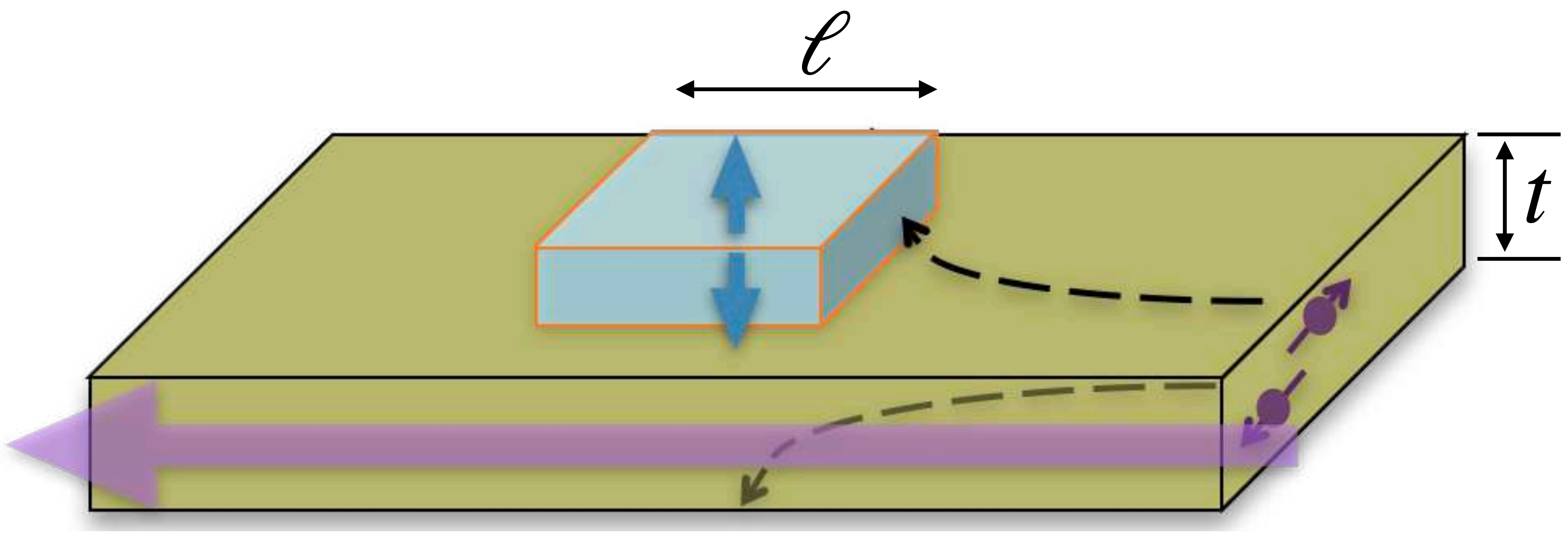
Polarization ⊗ Flow direction

Spin torque foundational theory 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)

Spin-orbit torques





$$J_s/J_c = \theta_{\mathrm{SH}}$$

$$I_s/I_c \simeq \theta_{\mathrm{SH}}(\ell/t)$$

$$\mathbf{Q} = \frac{-\hbar}{\mathbf{2e}}\xi\sigma_{\mathrm{SHE}}(\hat{z}\times\mathbf{E}) \otimes \hat{z}$$

Polarization ⊗ Flow direction

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

Review articles: J. Sinova *et al.*, Spin Hall Effects, RMP **87**, 1213 (2015)
V. Amin *et al.*, Interfacial SOT, J. Appl. Phys. **128**, 151101 (2020)
C. Safranski, J. Z. Sun & ADK, Appl. Phys. Lett. **120**, 160502 (2022)

Spin Dynamics: LLG+Spin-Torque (LLGS)

Landau-Lifshitz-Gilbert-Slonczewski Eqn:

$$\frac{d\hat{m}}{dt} = \underbrace{-\gamma\mu_0\hat{m}\times\vec{H}_{\mathrm{eff}}}_{\text{precession}} + \underbrace{\alpha\hat{m}\times\frac{d\hat{m}}{dt}}_{\text{damping}} + \underbrace{\gamma a_J\hat{m}\times(\hat{m}\times\hat{m}_P)}_{\text{spin torque}}$$

Nonlinear dynamics!

“adiabatic STT”

$$-[\hat{m}_\mathsf{p} - (\hat{m}\cdot\hat{m}_\mathsf{p})\hat{m}]$$

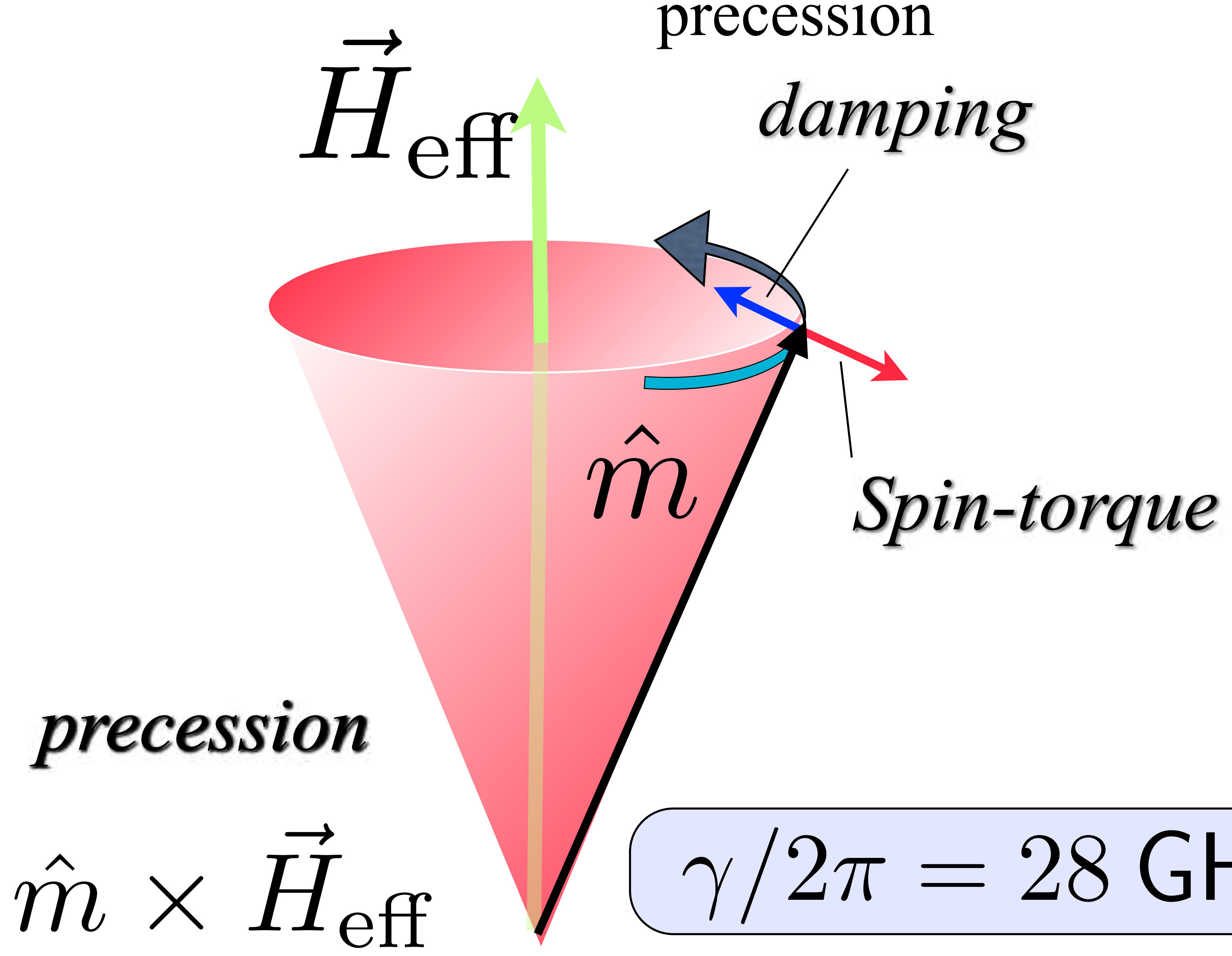
$$a_J = \frac{\hbar P I}{2eM_\mathsf{s}V}$$

When the spin-torque exceeds the damping instabilities occur

Also: $b_J\hat{m}\times\hat{m}_P$

“non-adiabatic STT”

‘Current-Induced Effective field’
Important in MTJs

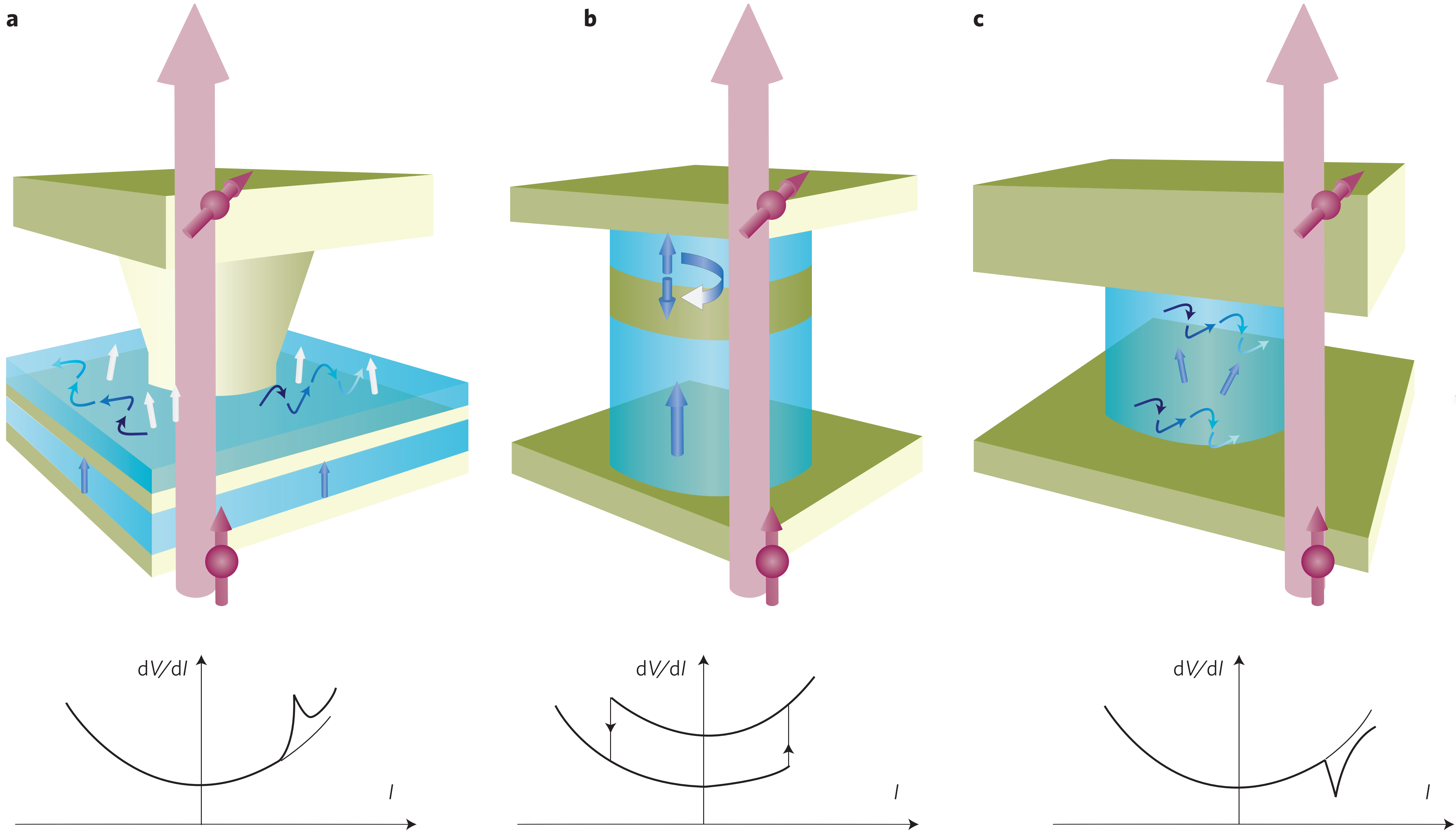


$\gamma/2\pi = 28\ \mathsf{GHz/T}$

- Fast dynamics is associated with the gyroscopic term
- Damping and spin transfer terms are smaller by a factor of ~100
- If $\boldsymbol{m_P}$ and $\boldsymbol{H_{eff}}$ are collinear the adiabatic spin-torque can act as an “anti-damping” torque
- The adiabatic spin-torque is zero when $\boldsymbol{m}$ and $\boldsymbol{m_P}$ are strictly collinear

Sample Geometries and Materials

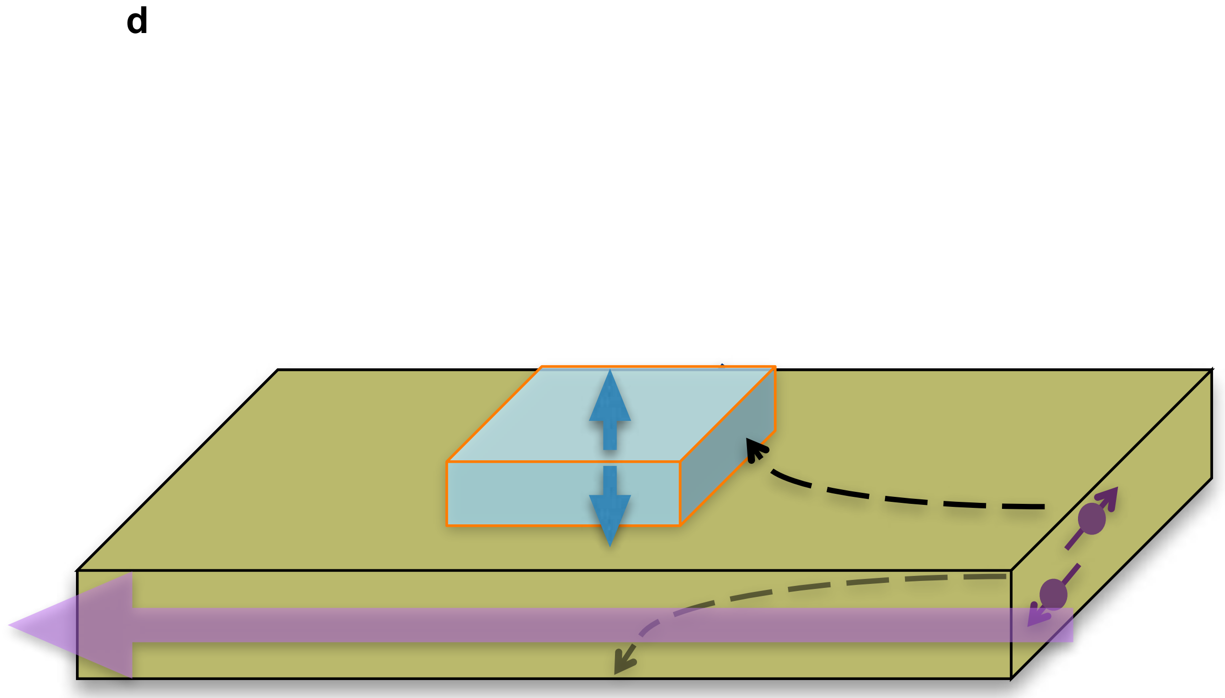
Important in nanostructures: Large current densities+STT dominate over Oersted fields



spin-torque nano-oscillators

nanopillars

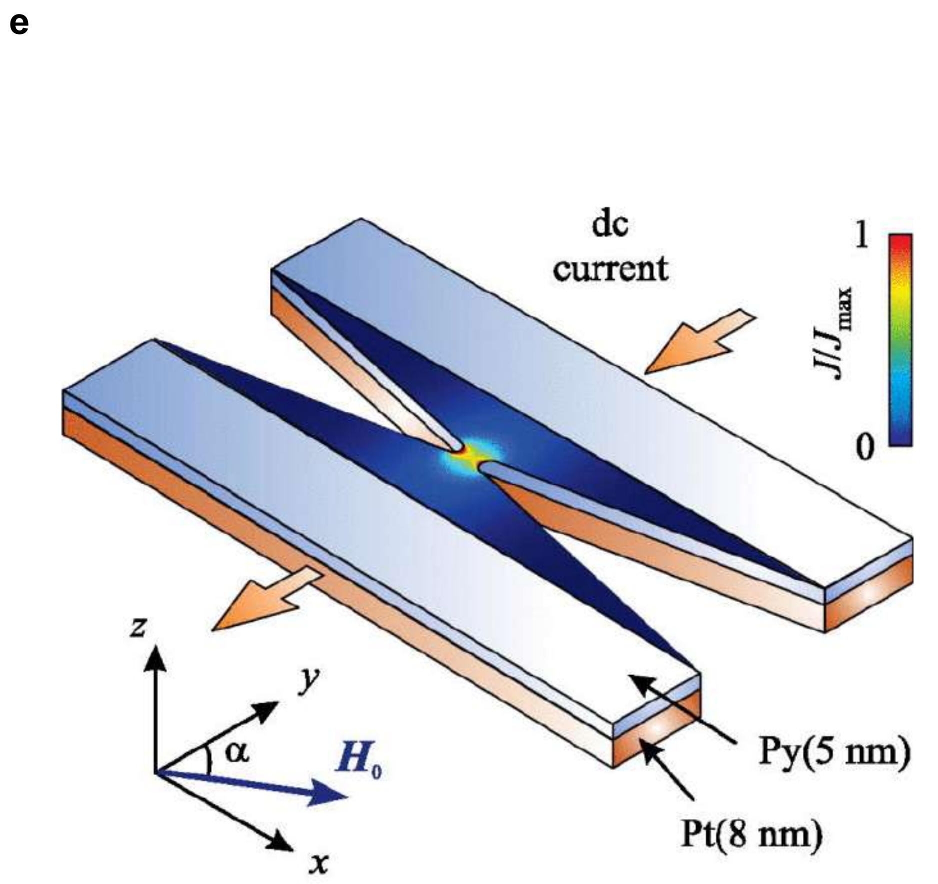
single layers



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

$$\frac{d\hat{m}}{dt} = \gamma\mu_0 \hat{m} \times \vec{H}_{\text{eff}} + \underbrace{\alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma a_J \hat{m} \times (\hat{m} \times \hat{p})}_{\text{STT can compensate damping in regions in the material}}$$

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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★]

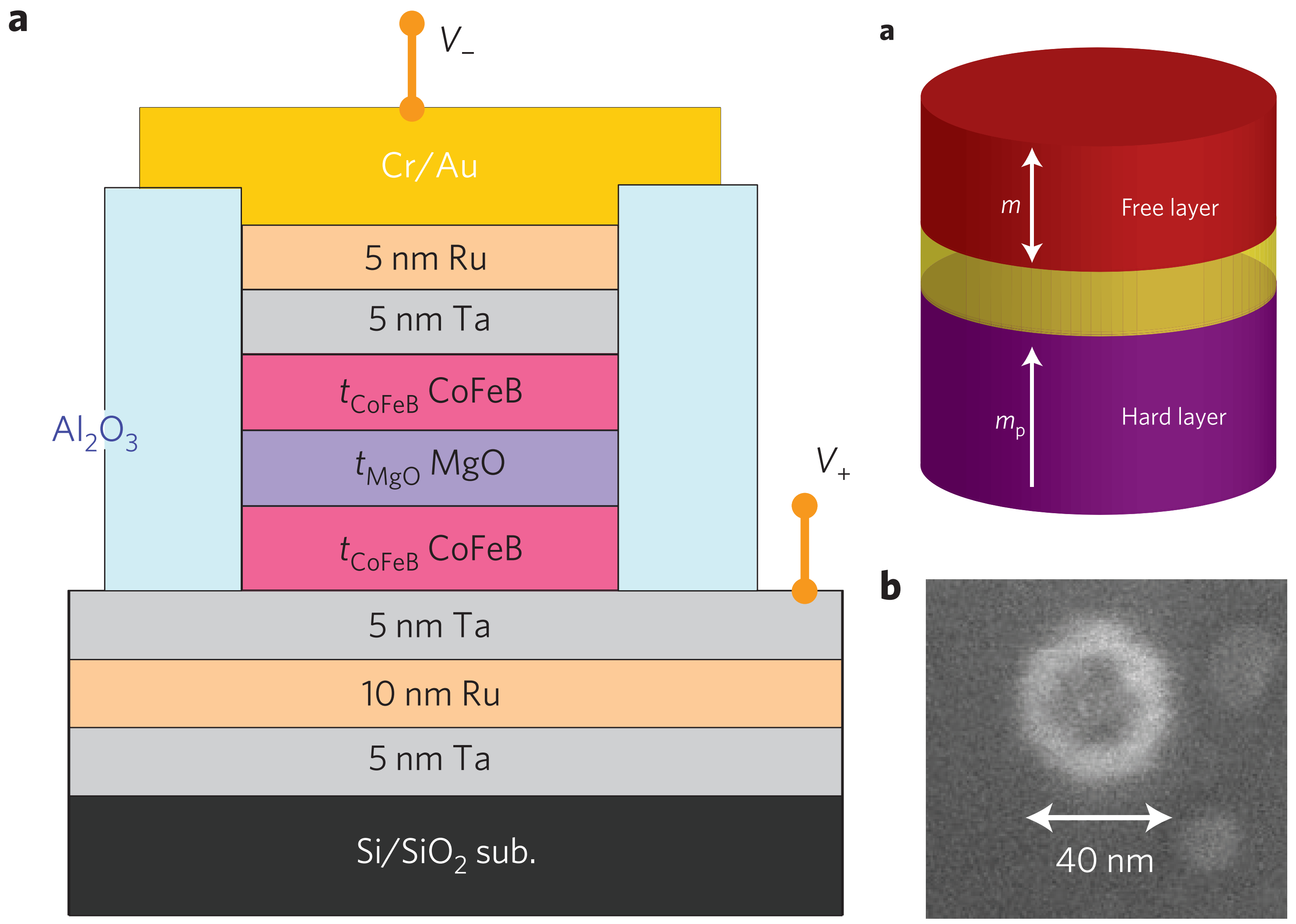
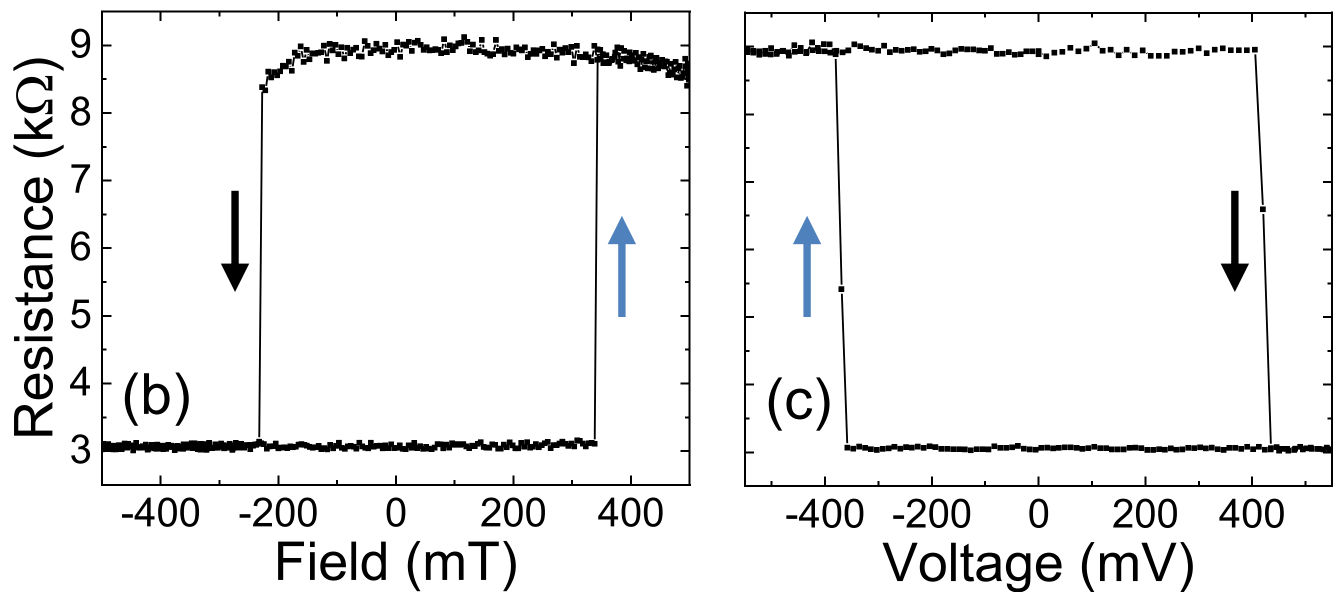


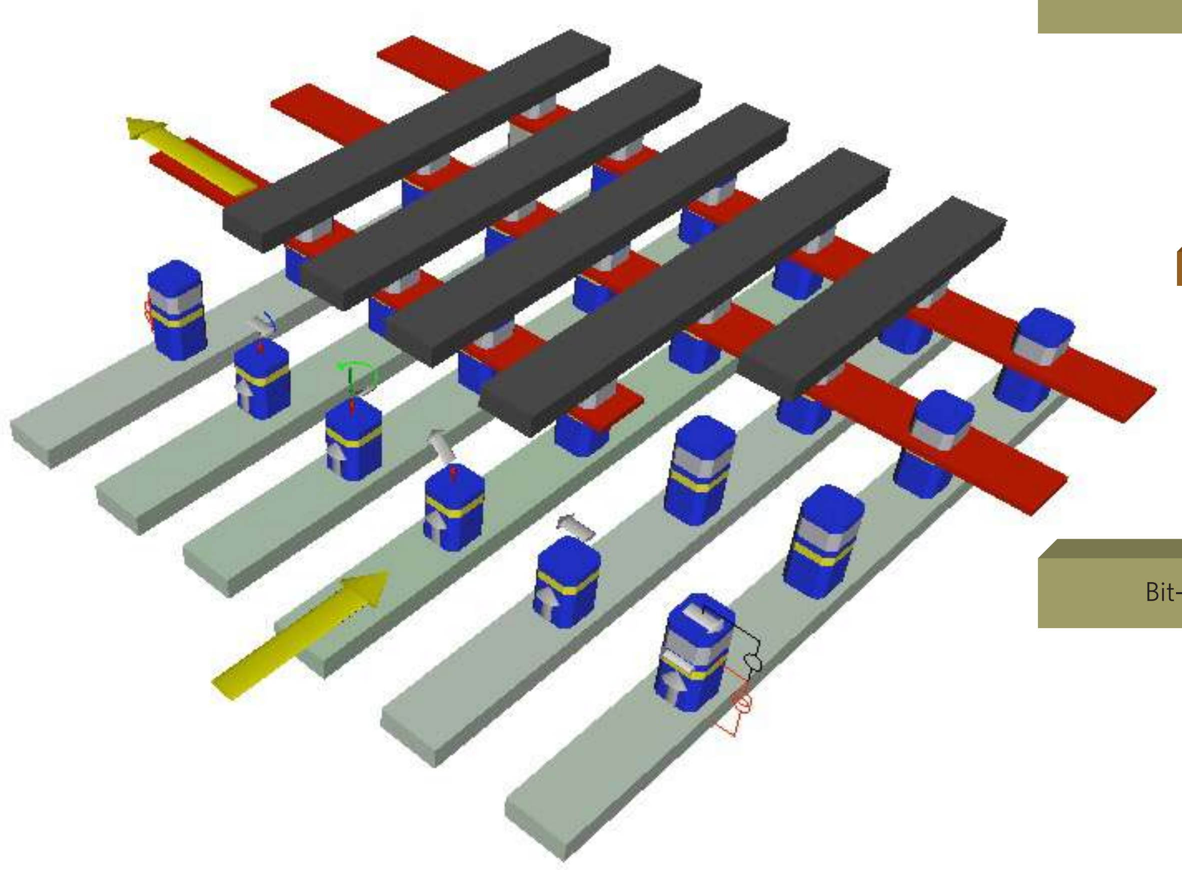
Figure 1 | MTJ structure. **a**, Schematic of an MTJ device for TMR and CIMS measurements. **b**, Top view of an MTJ pillar taken by scanning electron microscope.

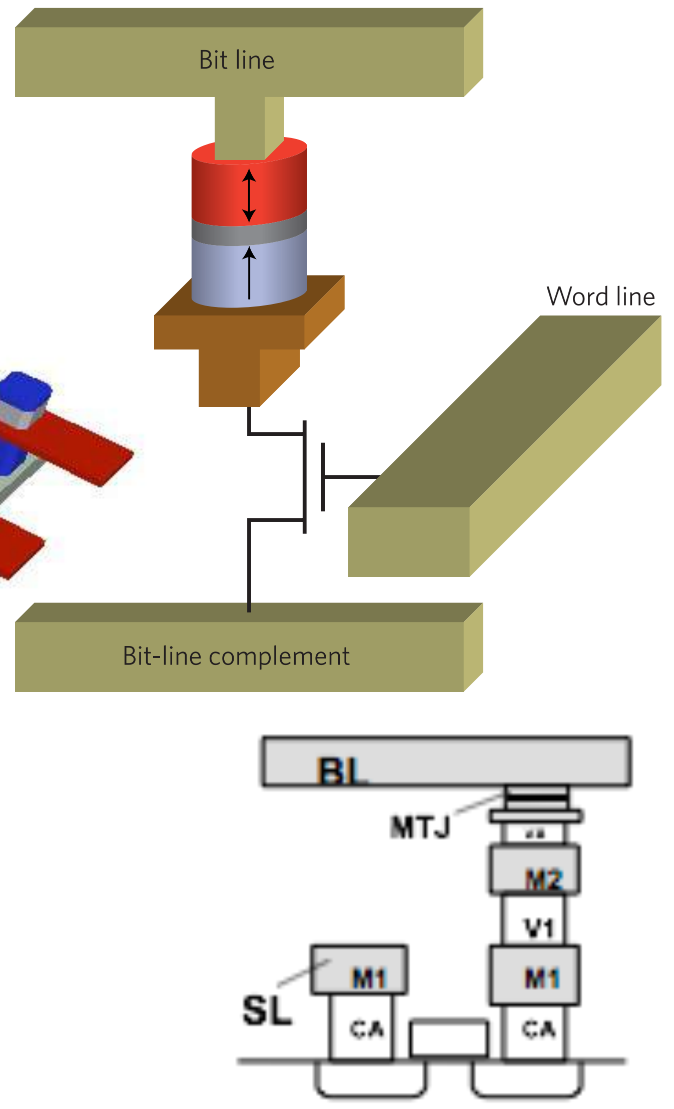


Field induced free layer switching

Current-induced switching

Applications: New types of MRAM



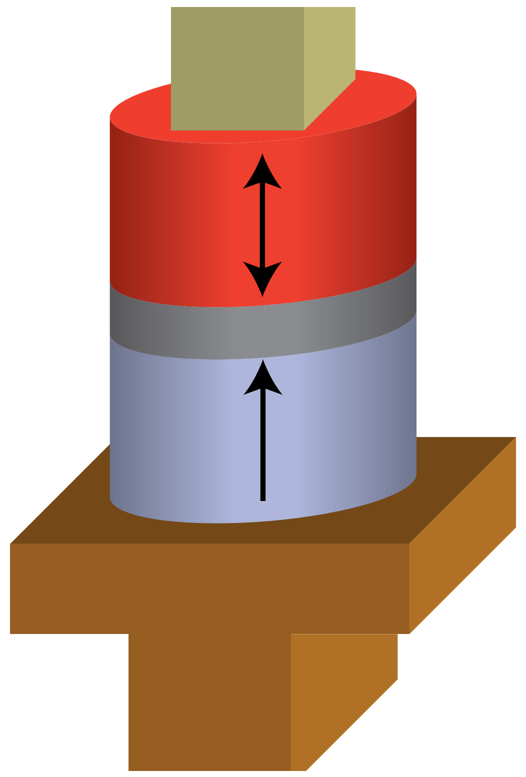


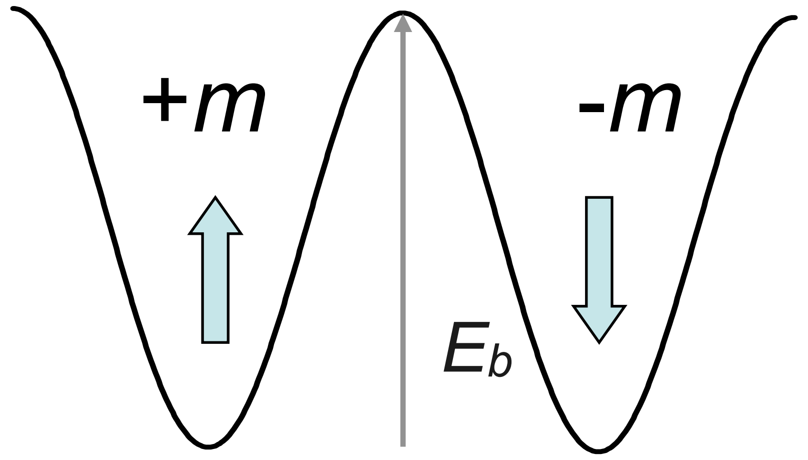
R. Beach et al., IEDM 2008

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

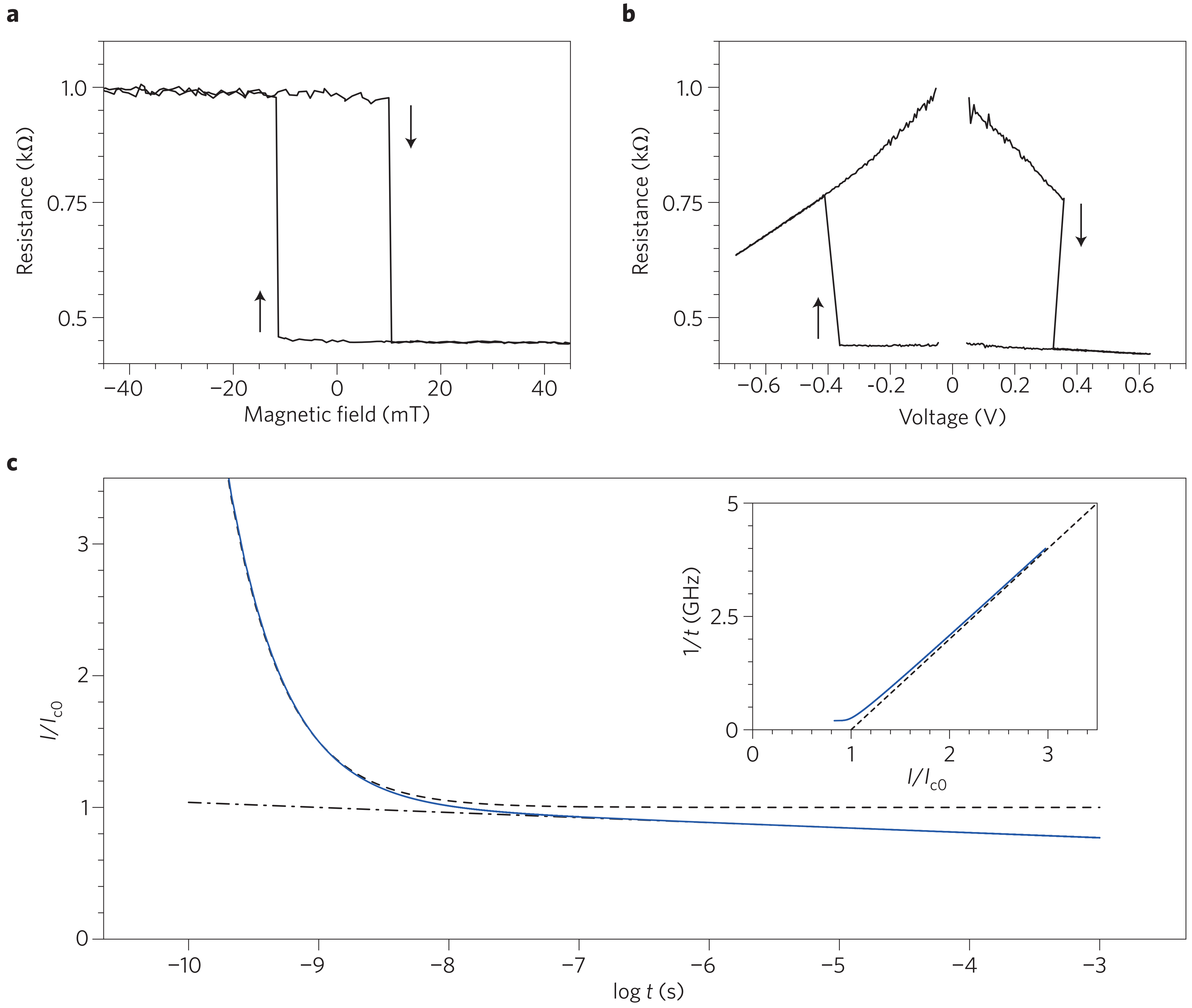
Perspective: A. D. Kent, Perpendicular all the way, Nature Materials **9**, 699 (2010)

Switching Magnetization of MTJ Nanopillars

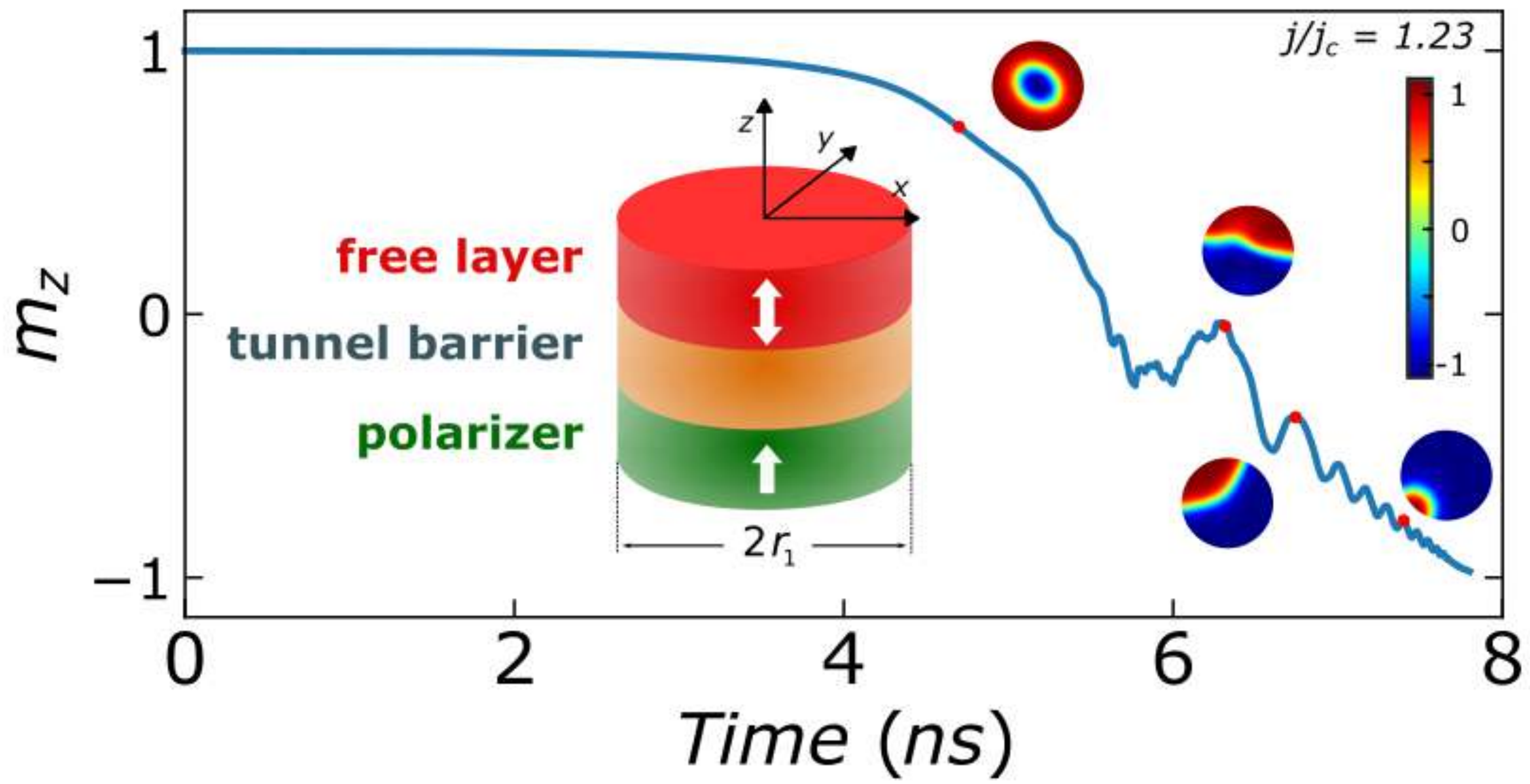




$$E_b/(kT) \gtrsim 60$$



Micromagnetic simulations

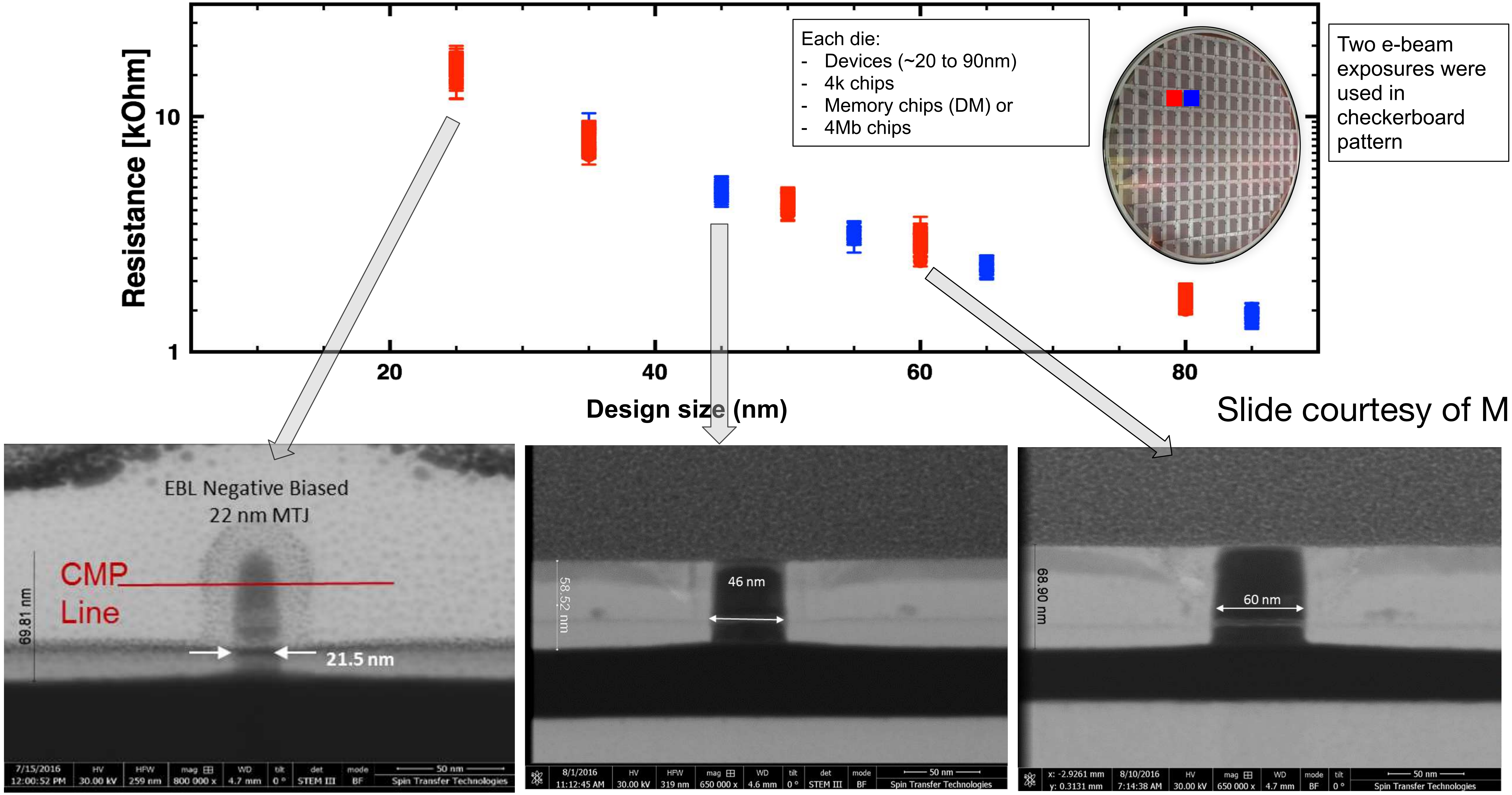


N. Statuto *et al.*, PRB **103**, 014409 (2021)
P. Bouquin *et al.*, APL **113**, 222408 (2018)
I. Volvach *et al.*, APL **116**, 192408 (2020)
J. B. Mohammadi *et al.*, APL **118**, 132407 (2021)

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

Magnetic Tunnel Junction Nanopillars

- Scaling down to 20 nm diameters

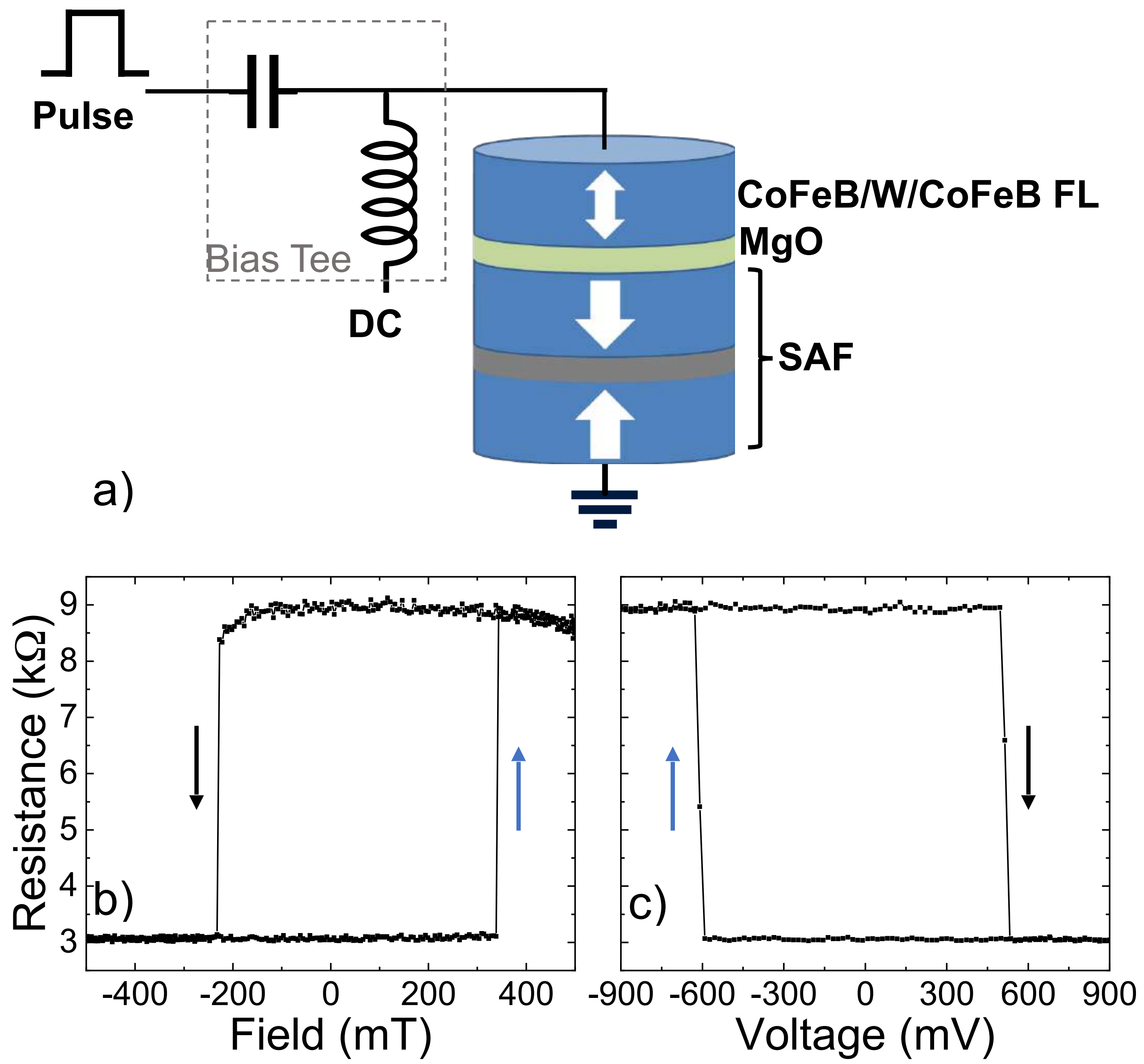


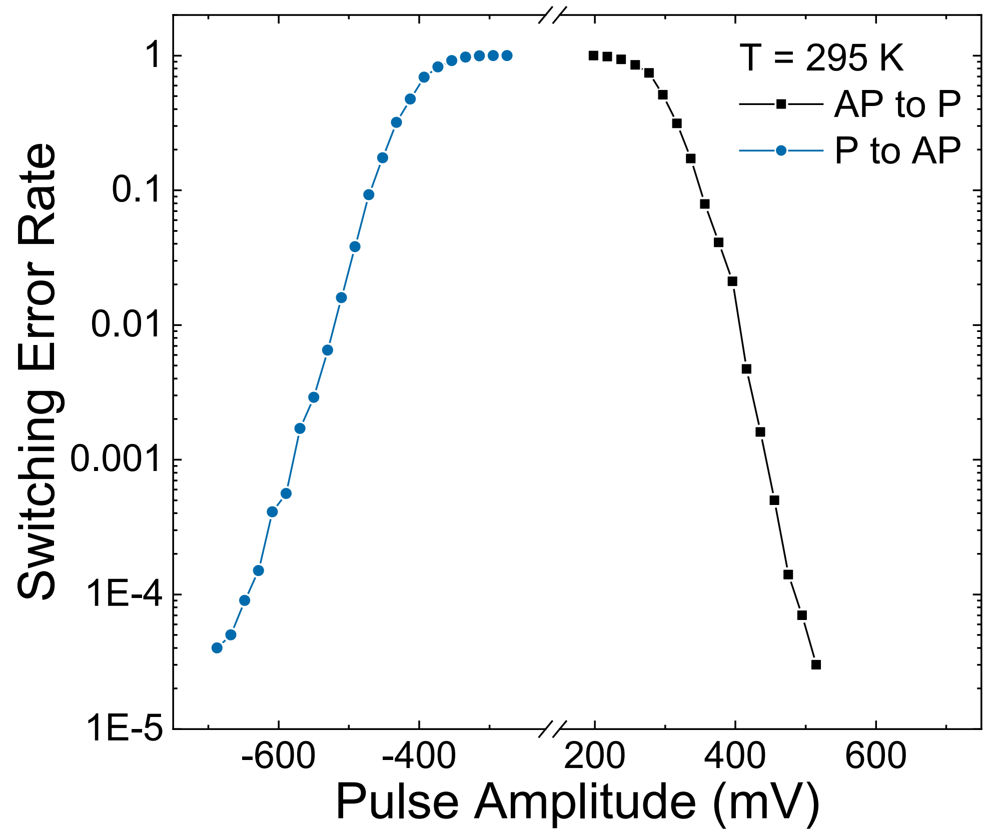
Each die:
- Devices (~20 to 90nm)
- 4k chips
- Memory chips (DM) or
- 4Mb chips

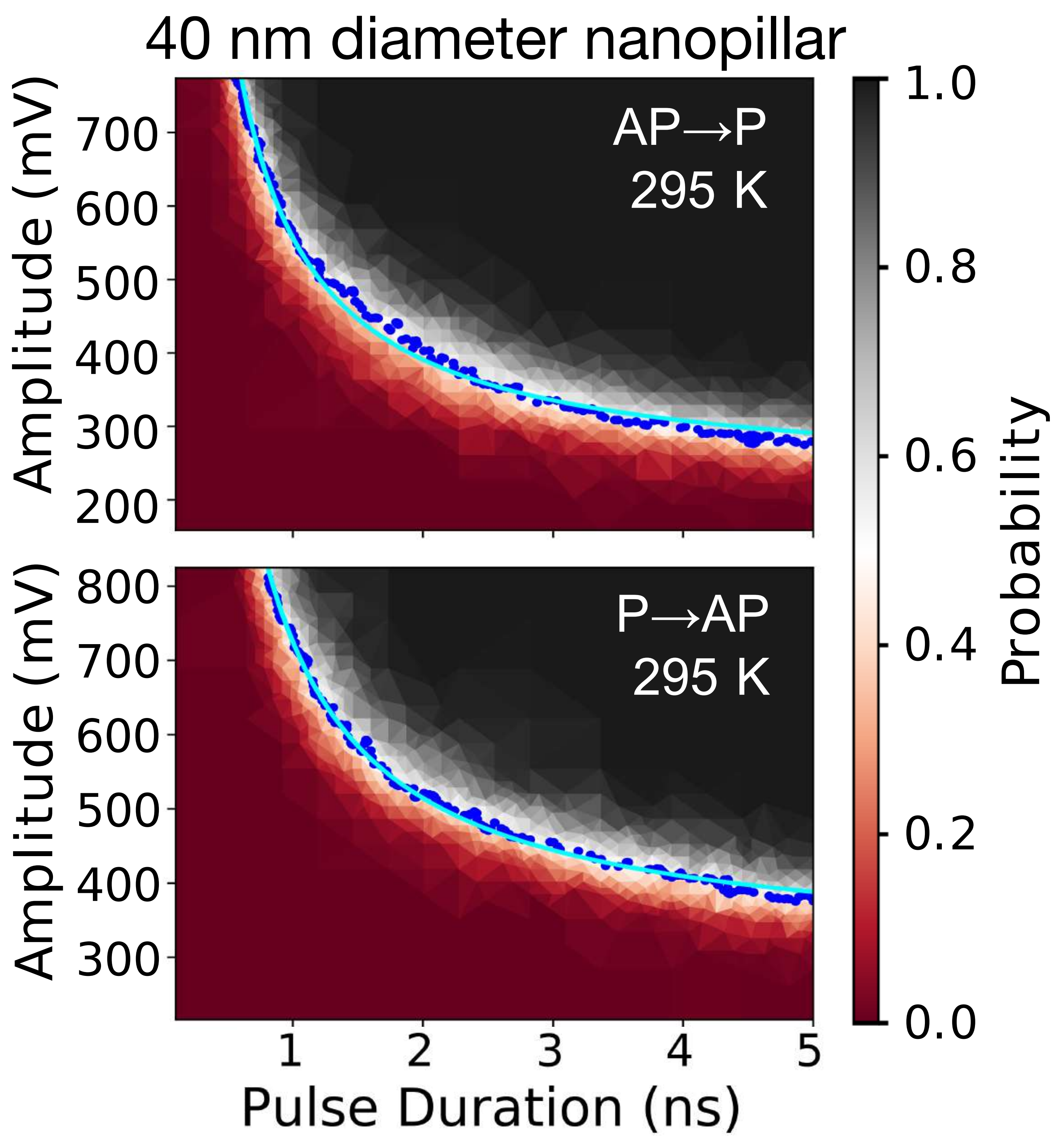
Two e-beam exposures were used in checkerboard pattern

Slide courtesy of Mustafa Pinarbasi

High Speed Magnetization Switching







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

critical number of transmitted charges N_c

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

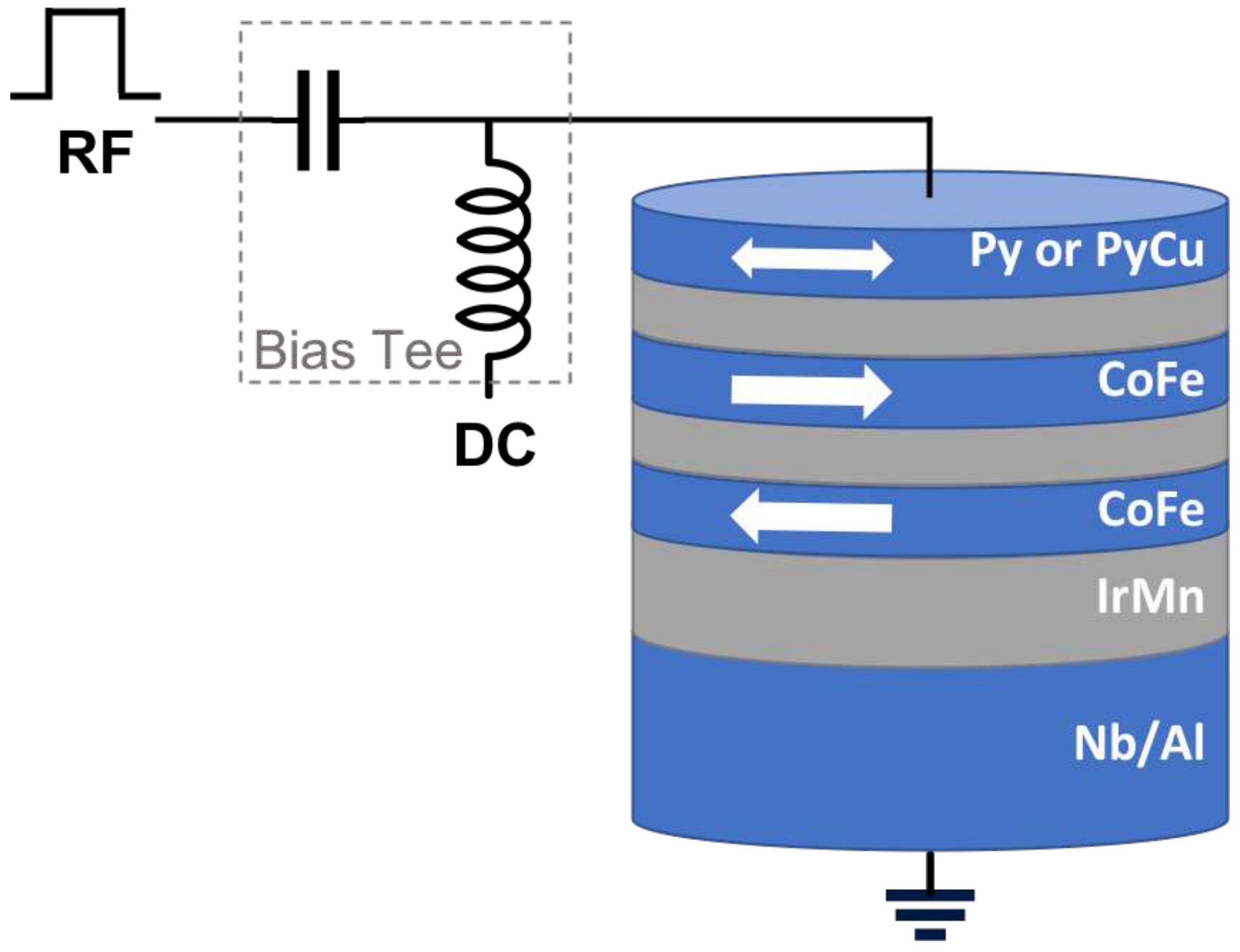
eN_c N dissipation

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

Laura Rehm *et al.,* Appl. Phys. Lett. **115**, 182404 (2019)
Laura Rehm *et al.,* Phys. Rev. Appl. **15**, 034088 (2021)

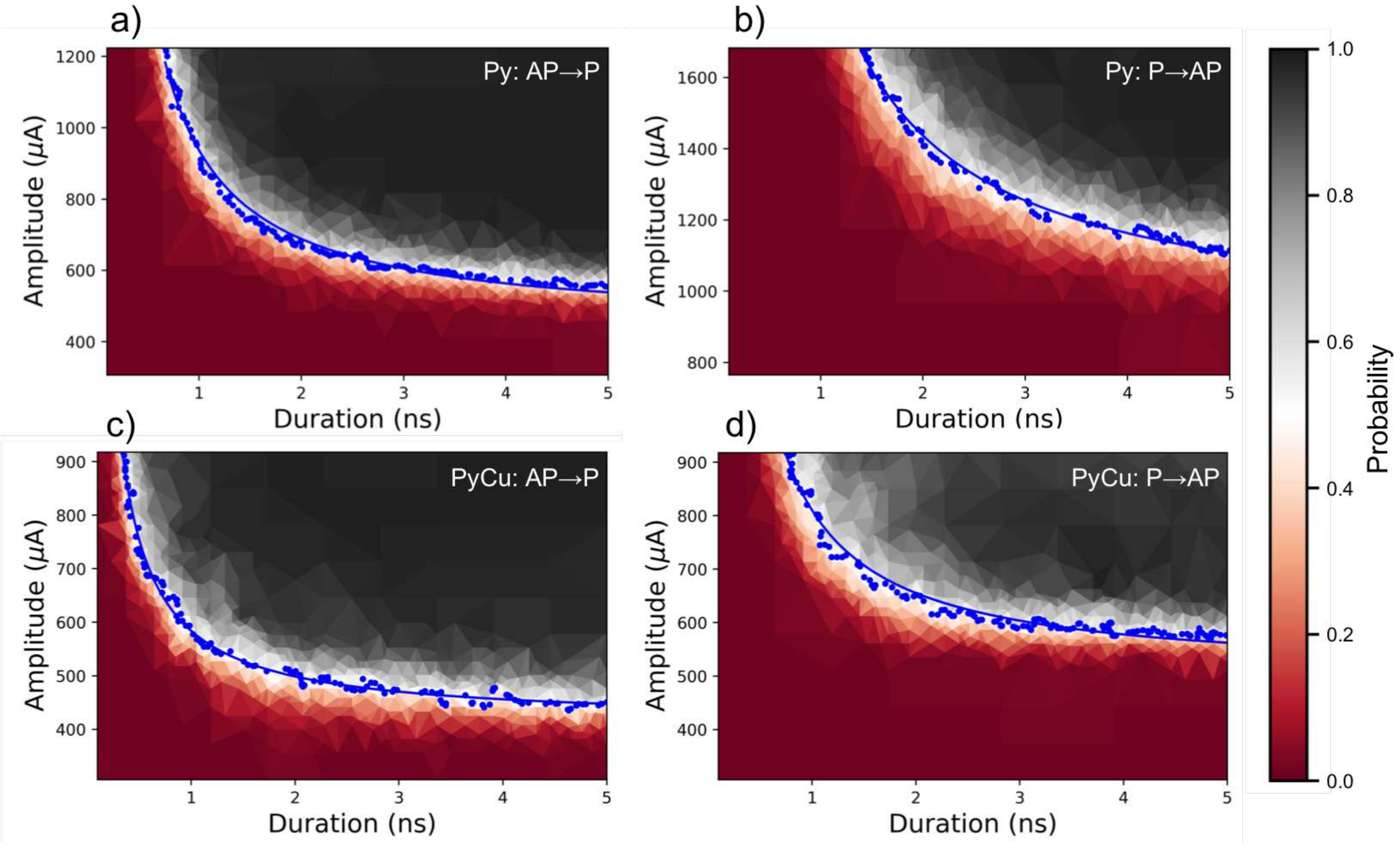
Reducing the Switching Energy

Reducing the magnetic moment of the free layer in a spin valve nanopillar



$50 \times 110\ \mathrm{nm}^2$

In-plane magnetized elliptical nanopillar

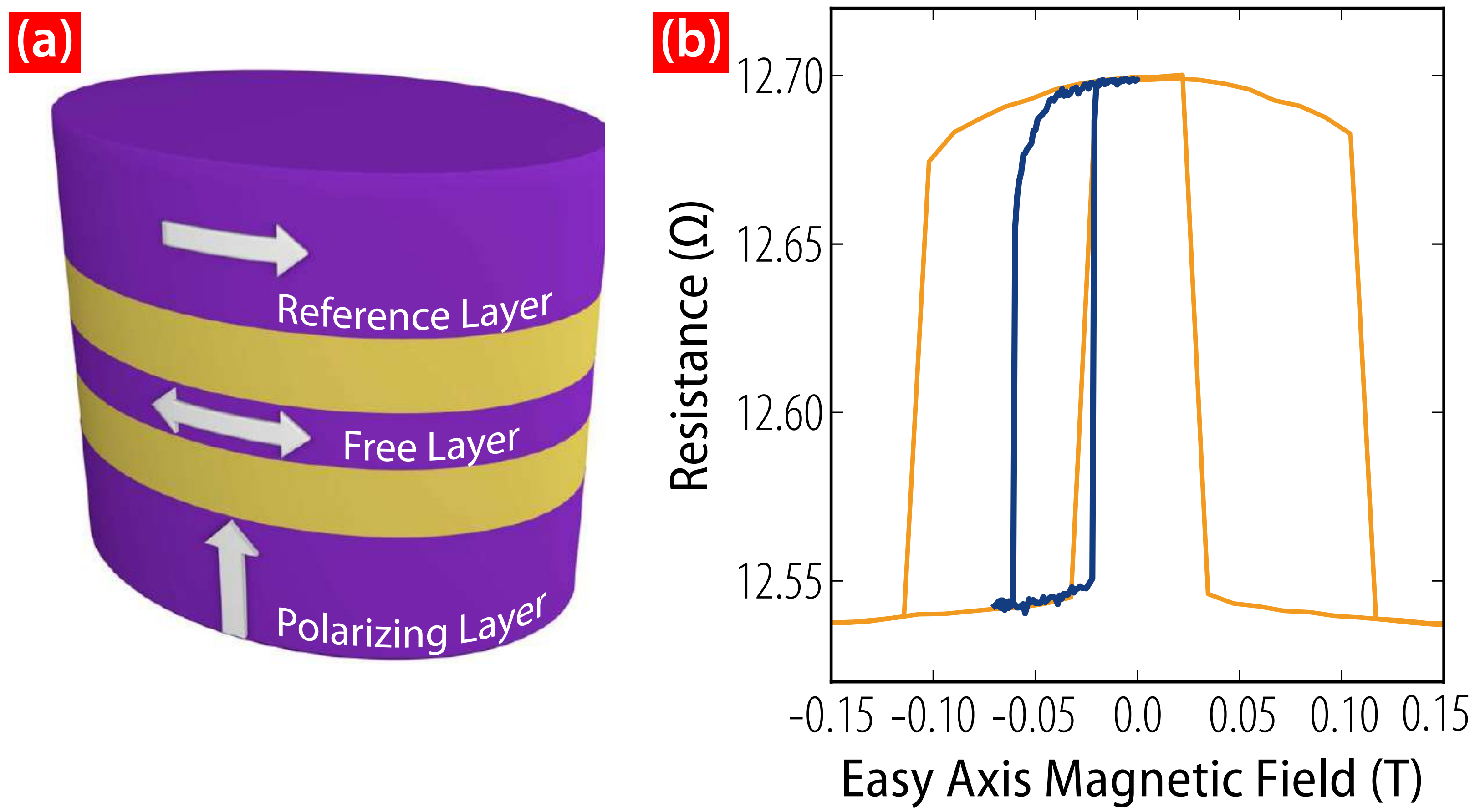


Sample	I_c (μA)		Λ	τ_0 (ns)	$\mu_0 M_{s,3.2K}$ (mT)
	AP → P	P → AP			
PyCu FL	395 ± 2	532 ± 2	1.16	0.475 ± 0.007	240
Py FL	432 ± 2	902 ± 3	1.44	1.18 ± 0.01	860

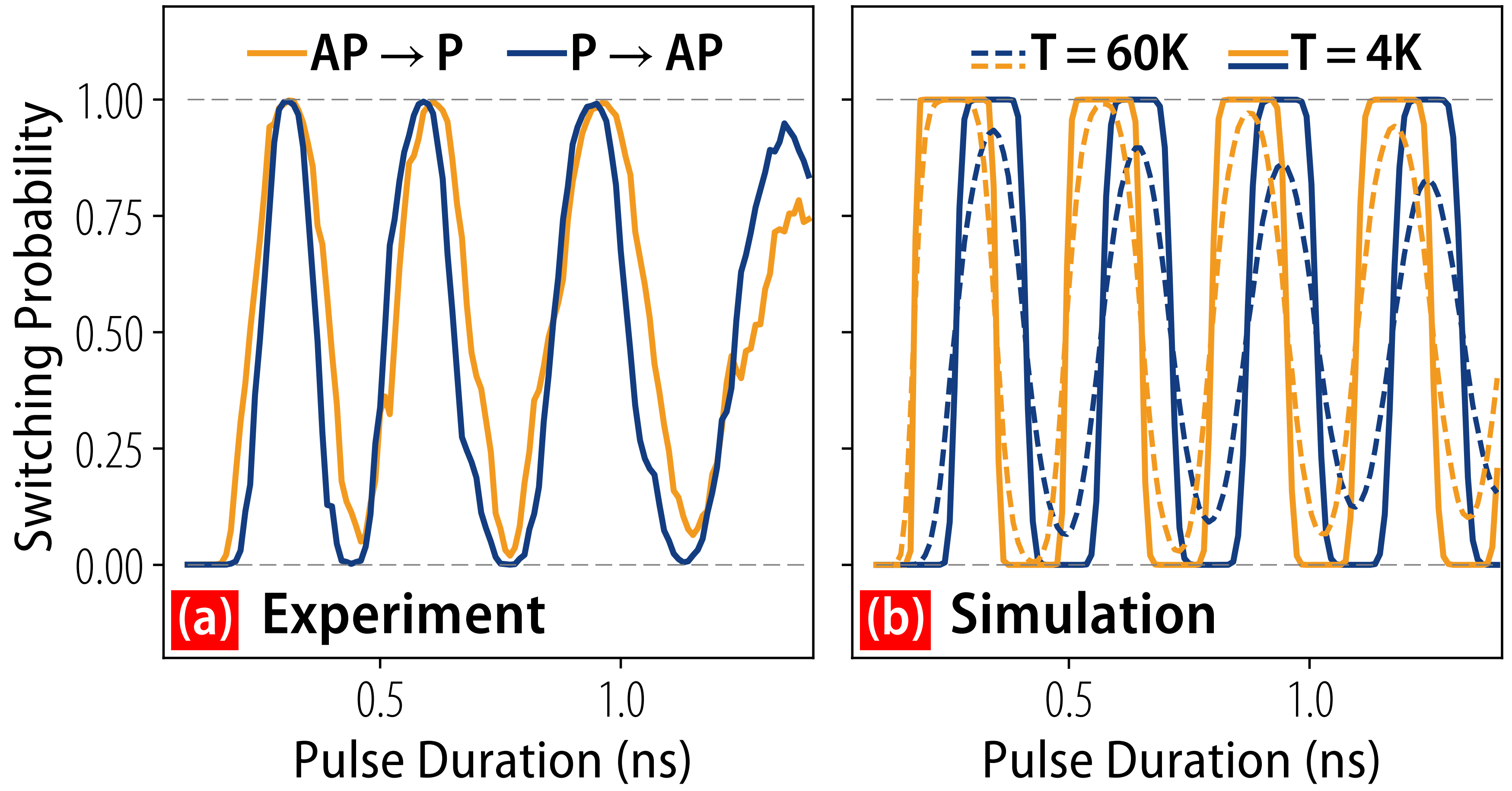
Write energy: $\lesssim 40\ \mathrm{fJ}$

L. Rehm, V. Sluka, G. E. Rowlands, M.-H. Nguyen, T. A. Ohki and A. D. Kent, Appl. Phys. Lett. **114**, 012404 (2019)

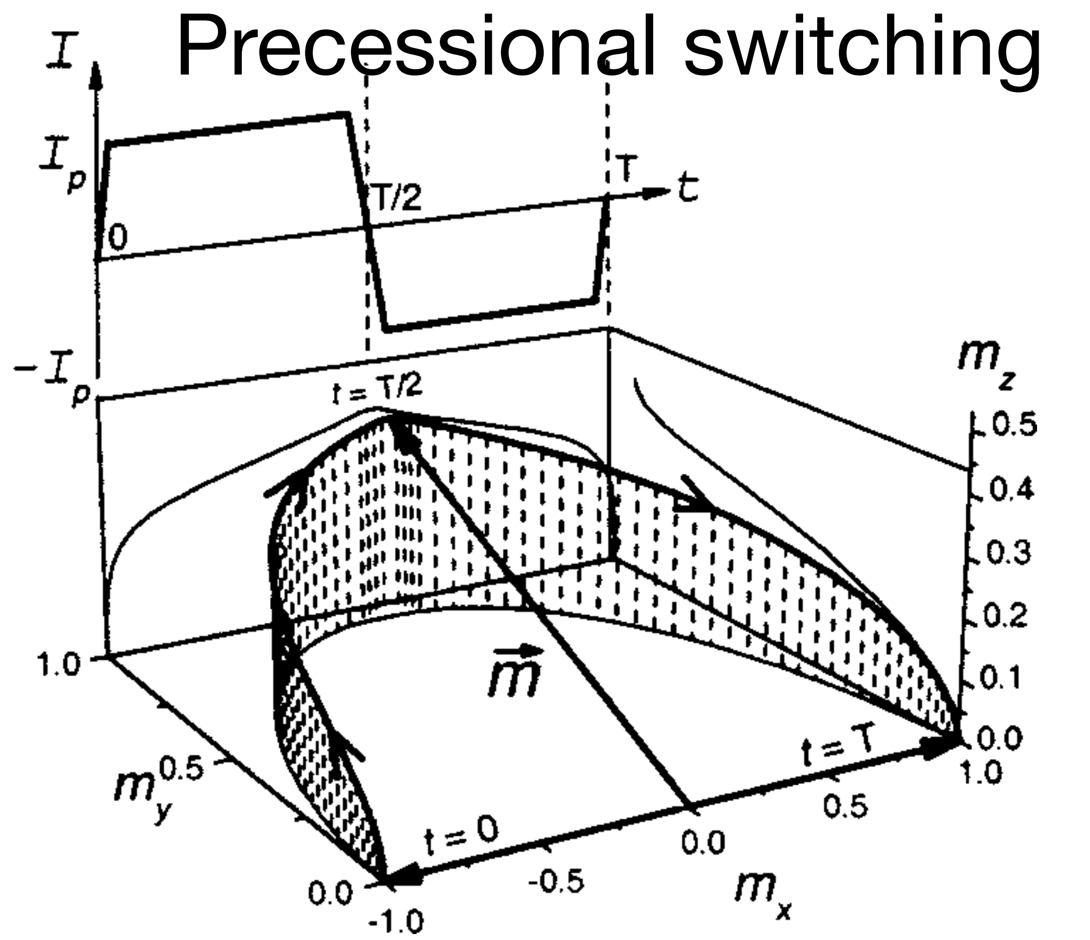
Increasing the Switching Speed



Orthogonal spin transfer torque device

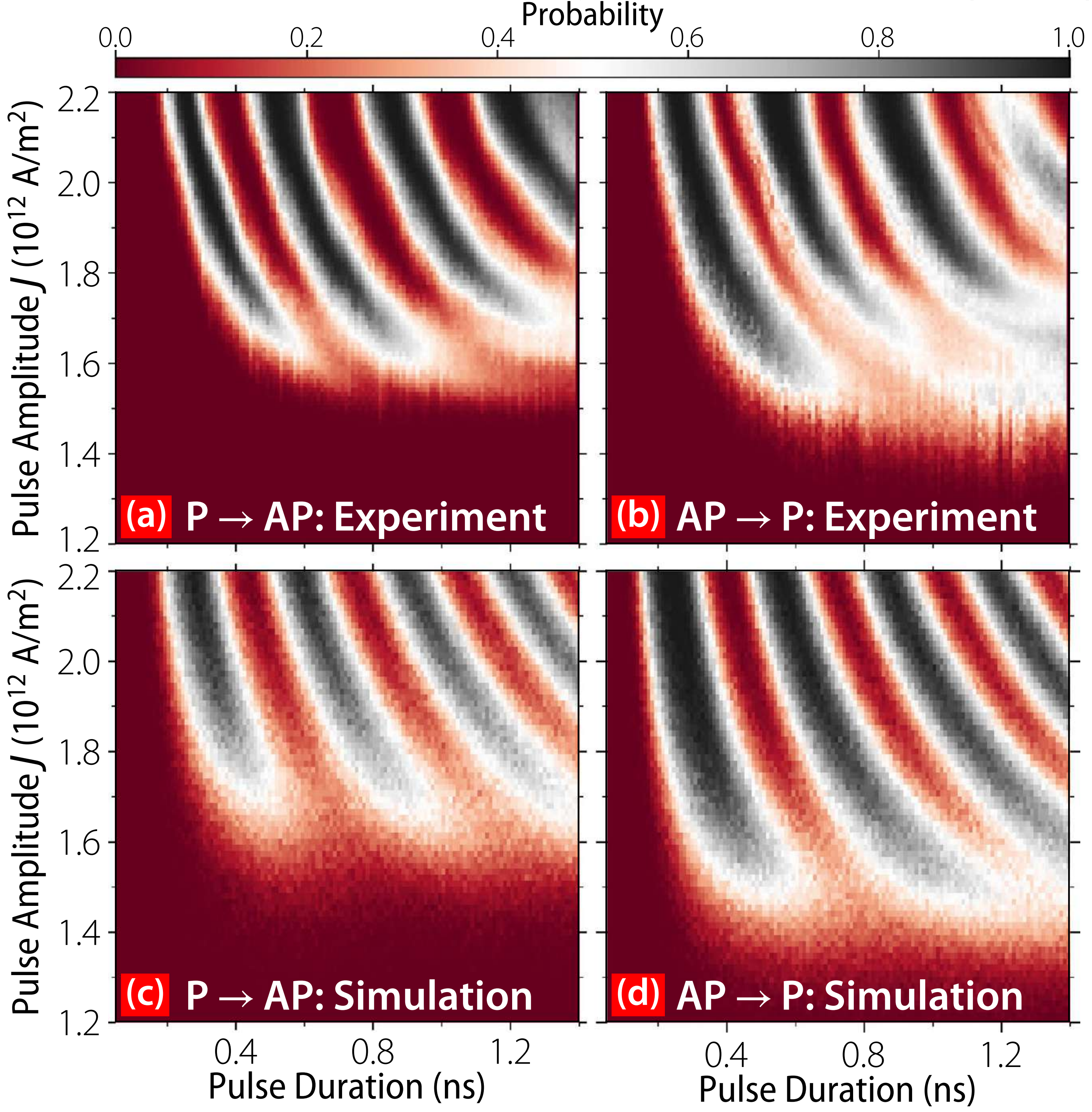


G. E. Rowlands *et al.*, Scientific Reports **9**, 803 (2019)



Precessional switching

A.D. Kent *et al.*, Appl. Phys. Lett. **84**, 3897 (2004)

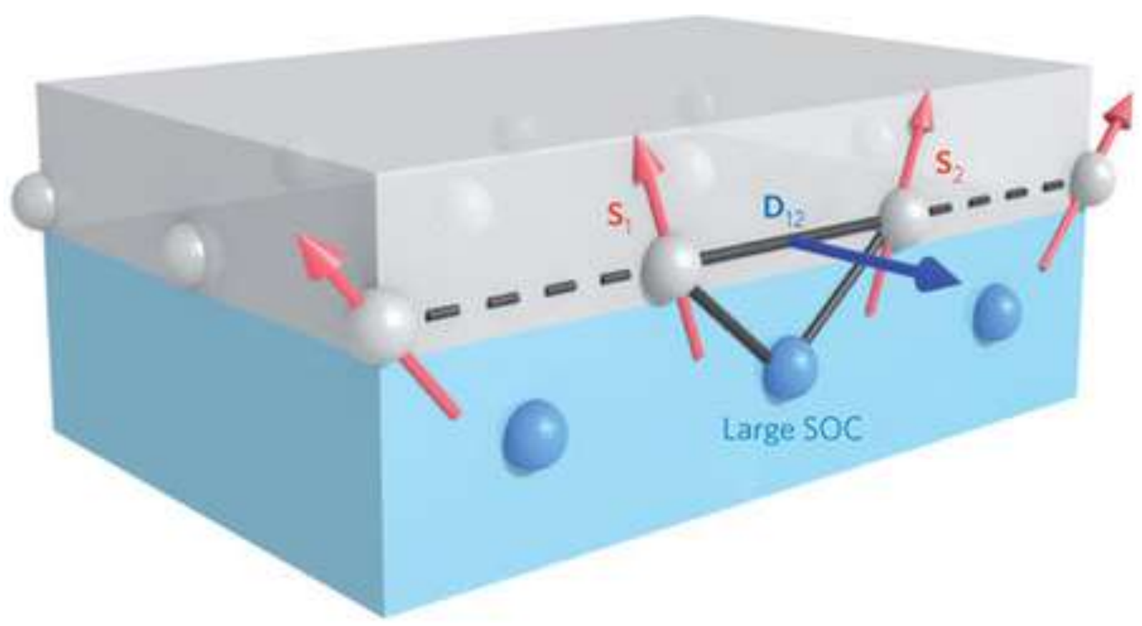


A New Spin on Magnetism with Applications in Information Processing

Outline

- Spintronics and spin-transfer torques
- Switching magnetization in magnetic tunnel junction nanopillars
- **Magnetic skyrmions**
- Center for Quantum Phenomena NYU NY

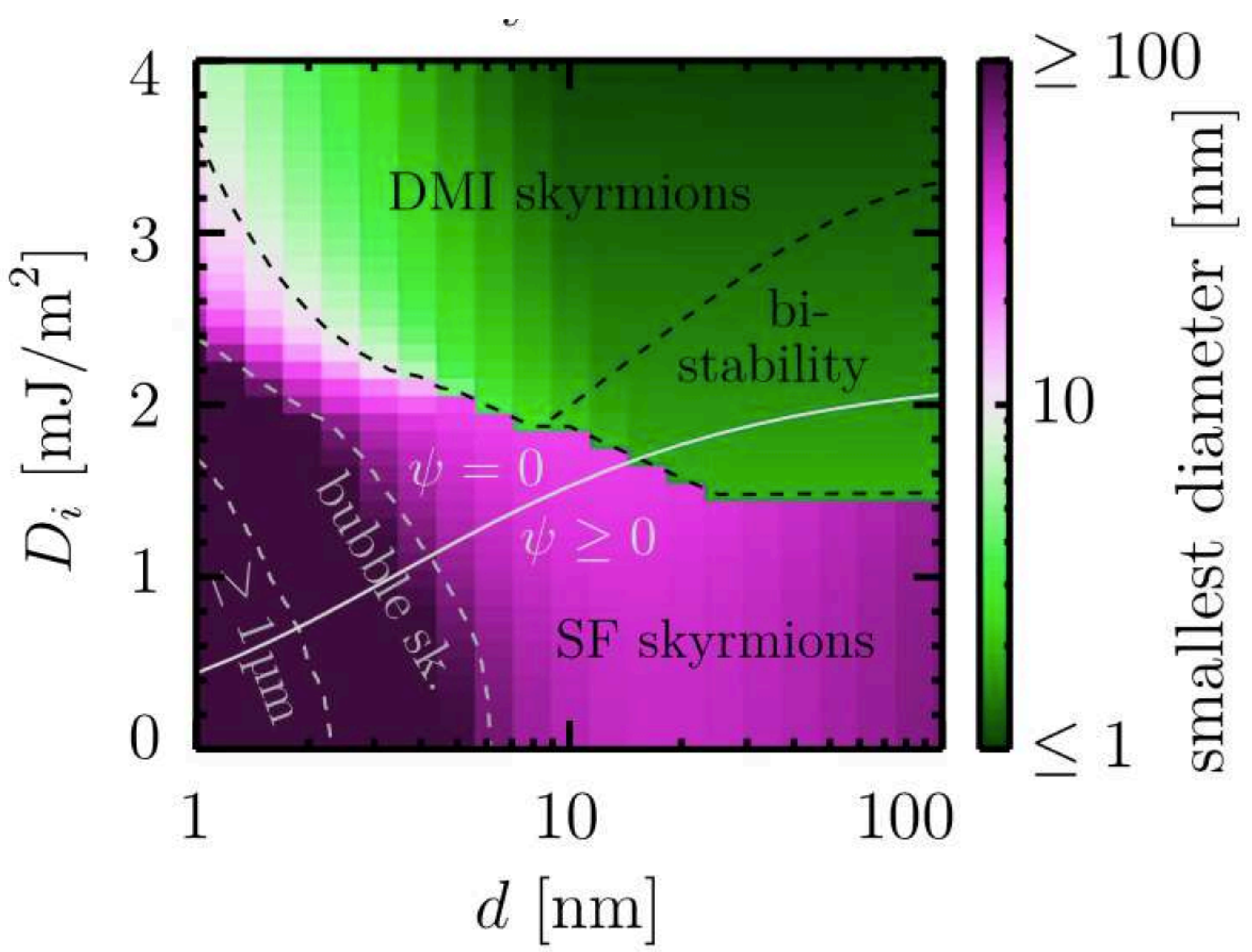
Magnetic Skyrmions



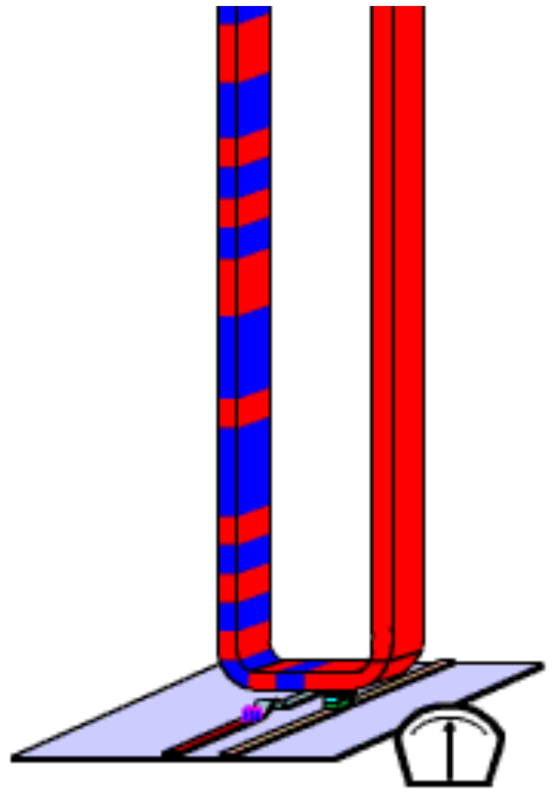
Néel-type skyrmion

Control magnetic interactions → Isolated skyrmions

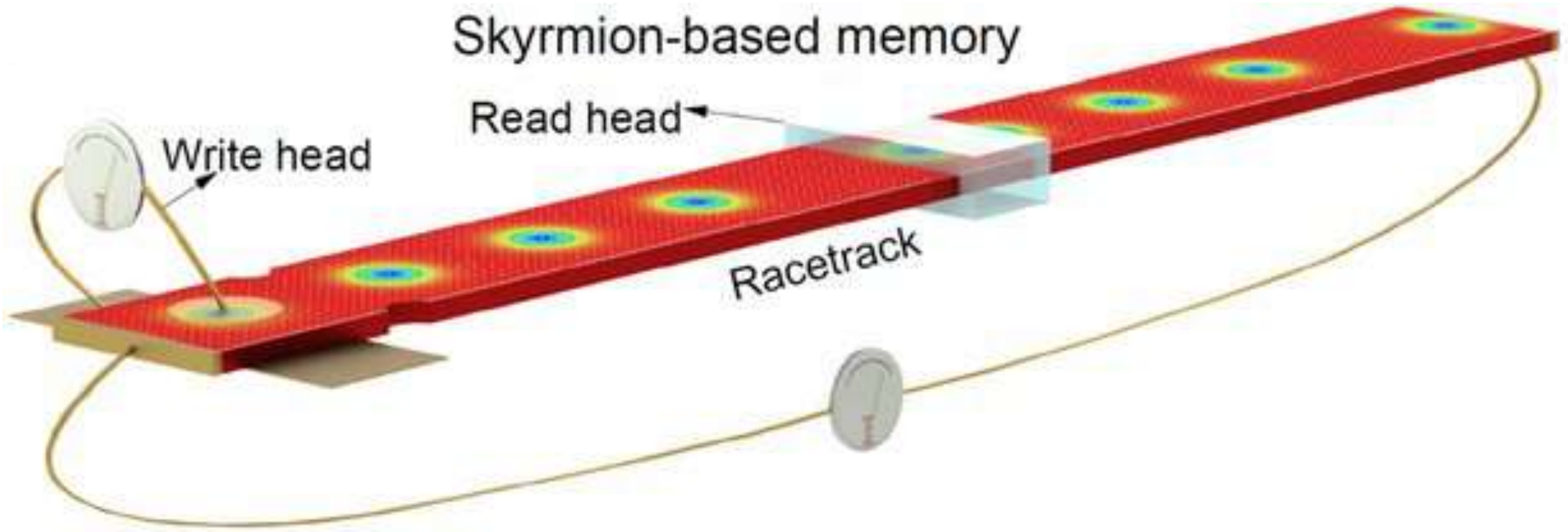
$$H = -\sum_{\langle ij \rangle} \left[J_{ij} \vec{S}_i \cdot \vec{S}_j - D_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right] - \sum_i K S_z^2$$



F. Büttner *et al, Scientific Reports* **8**, 4464 (2018)

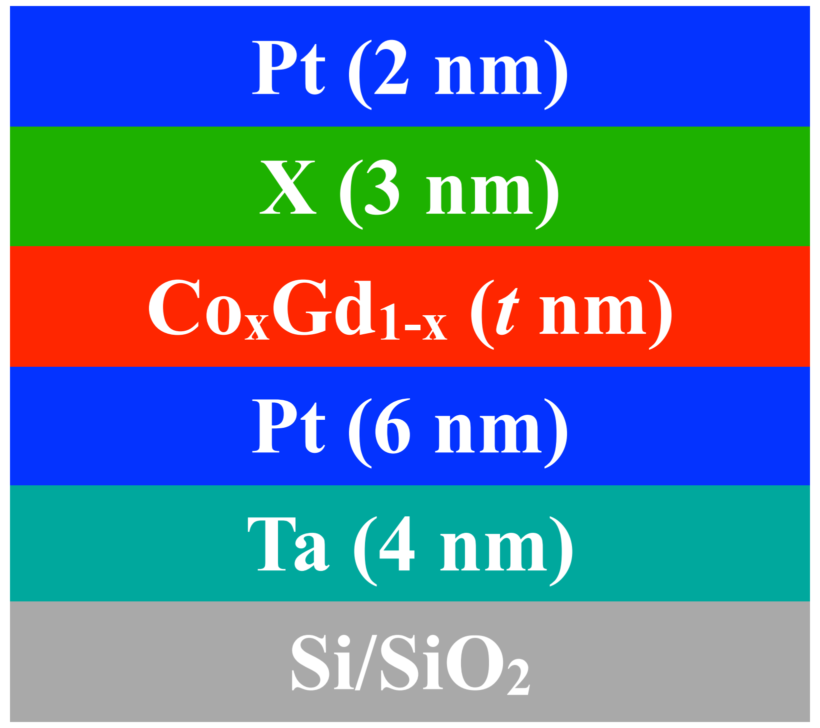


DW racetrack memory
Skyrmion racetrack memory



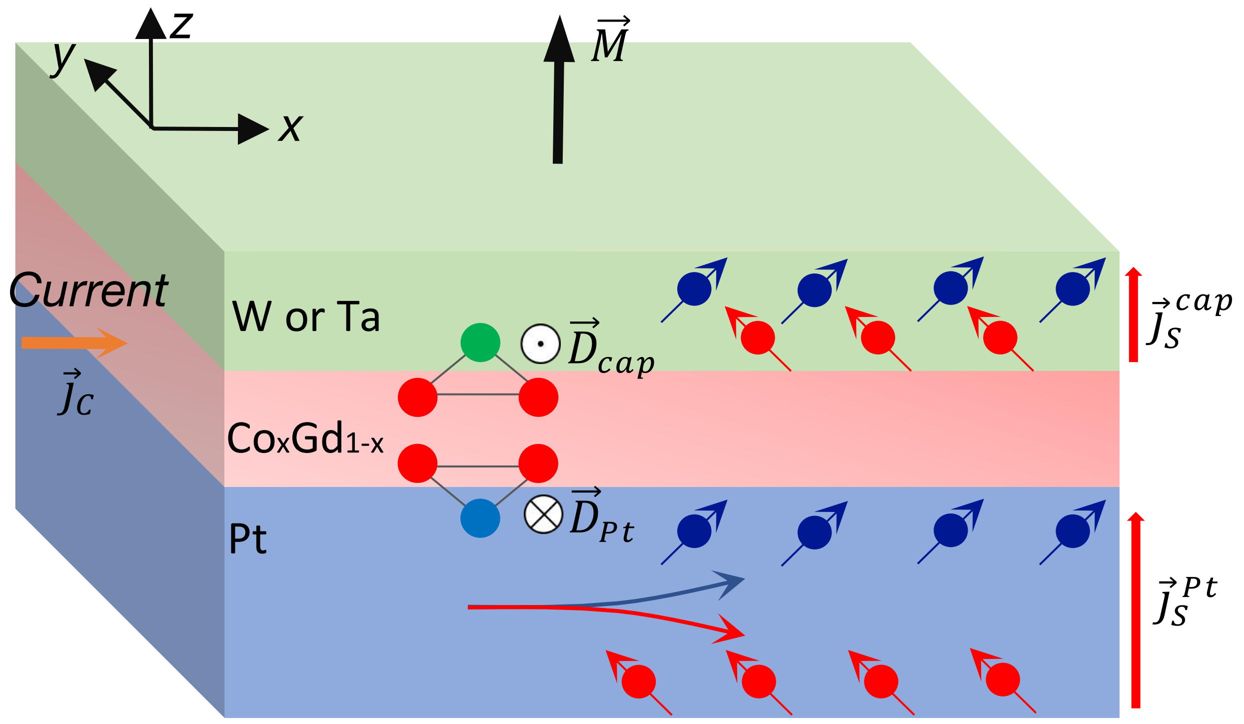
Growth and characterization of ferrimagnetic CoGd thin films

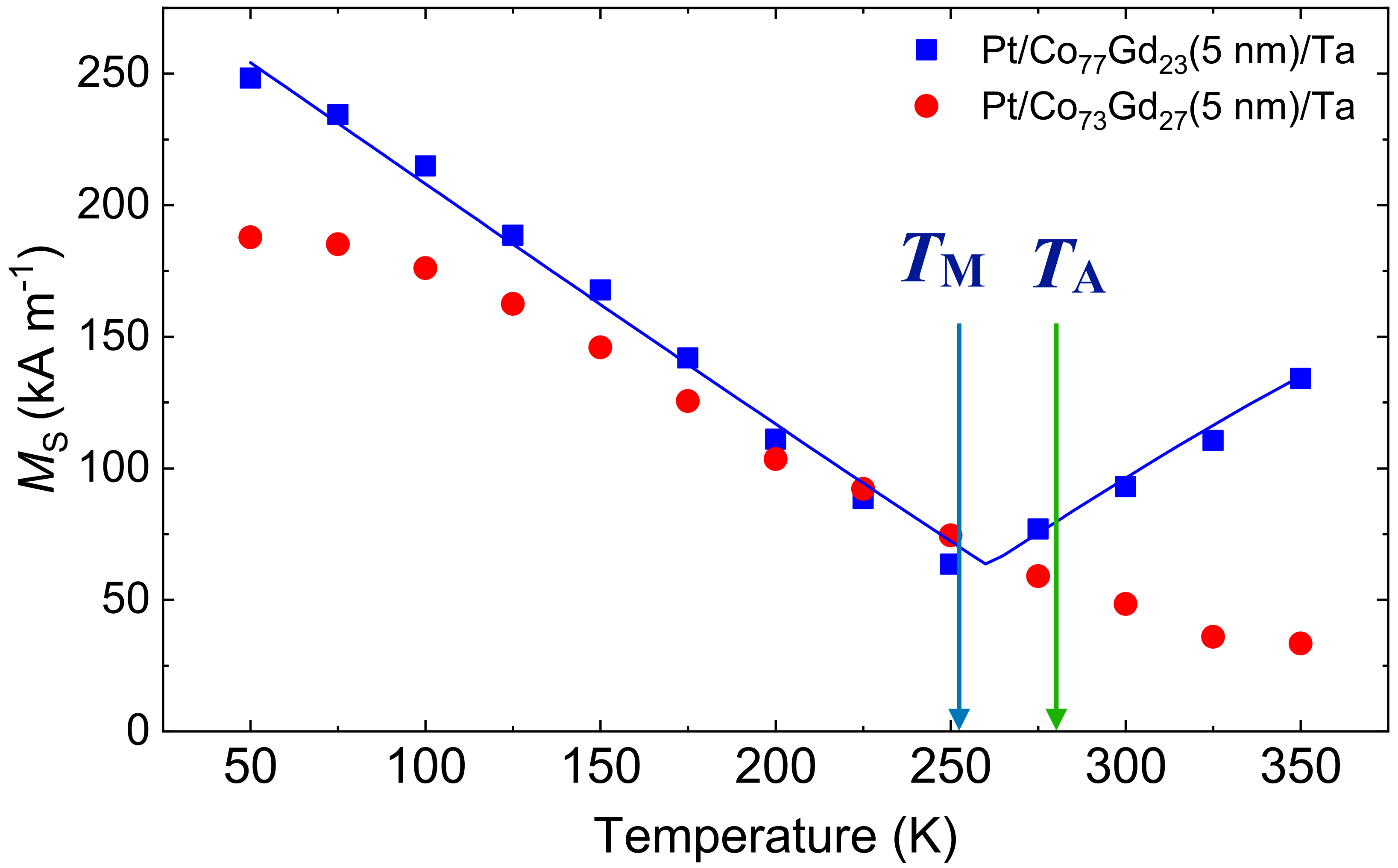
- **Control of the DMI and SOTs** is important to improve current-induced skyrmion motion.
- Study[2] of a trilayer system to simultaneously vary DMI and SOTs (θ_{SHE}).
- Bottom and top HM layer are sources of:
  - ➠ Spin-Orbit Coupling (⇒ DMI, stability of SKs)
  - ➠ Spin currents (⇒ enhanced dynamics)
- CoGd alloy compositions were chosen in a way that:
  - ➠ Low M_s i.e. T_M close to RT ideal for small SKs
  - ➠ T_A close to RT: fast spin dynamics



Pt (2 nm)
X (3 nm)
Co_xGd_{1-x} (t nm)
Pt (6 nm)
Ta (4 nm)
Si/SiO_2

X = Ta, W or Ir





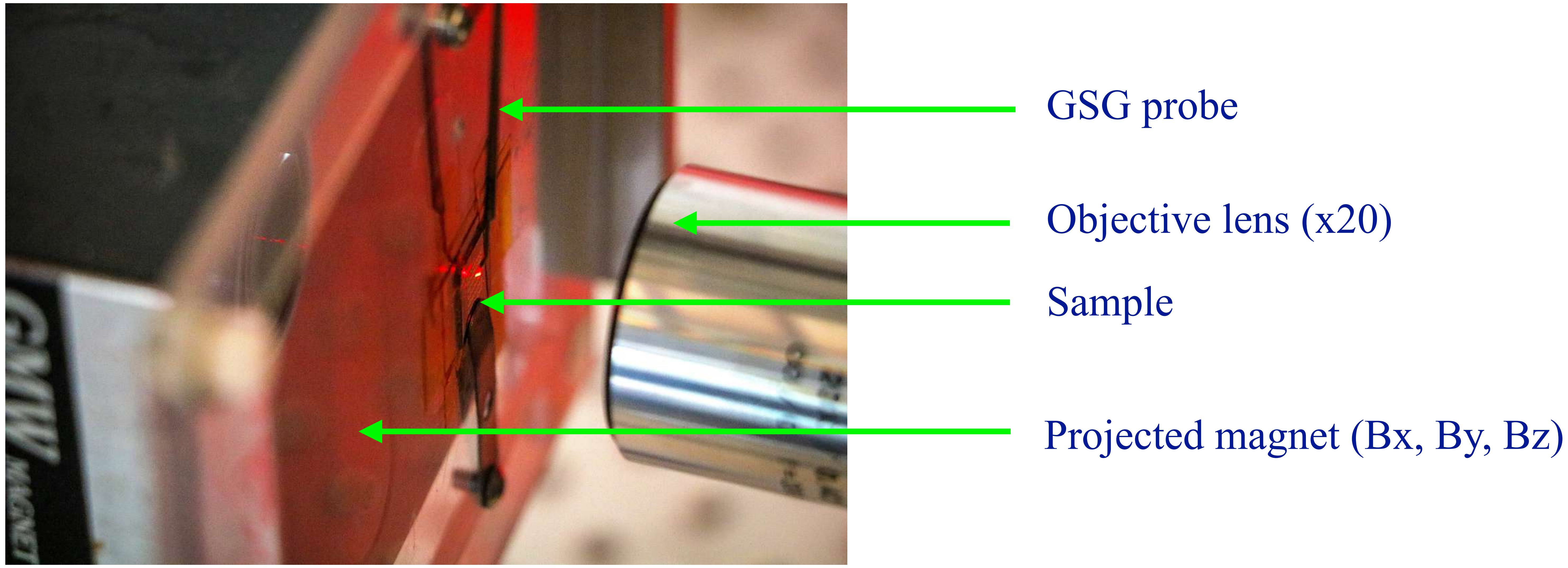
Capping layer	x_{Co} [%]	M_S [kA m^{-1}]	K_U [kJ m^{-3}]	T_M [K]	T_A [K]
Ta	77	93	18.0	250	285
Ta	73	48	9.5	337	361
W	77	132	26.7	250	292
W	73	65	8.6	367	391
Ir	77	188	38.3	150	174
Ir	73	38	7.4	300	325

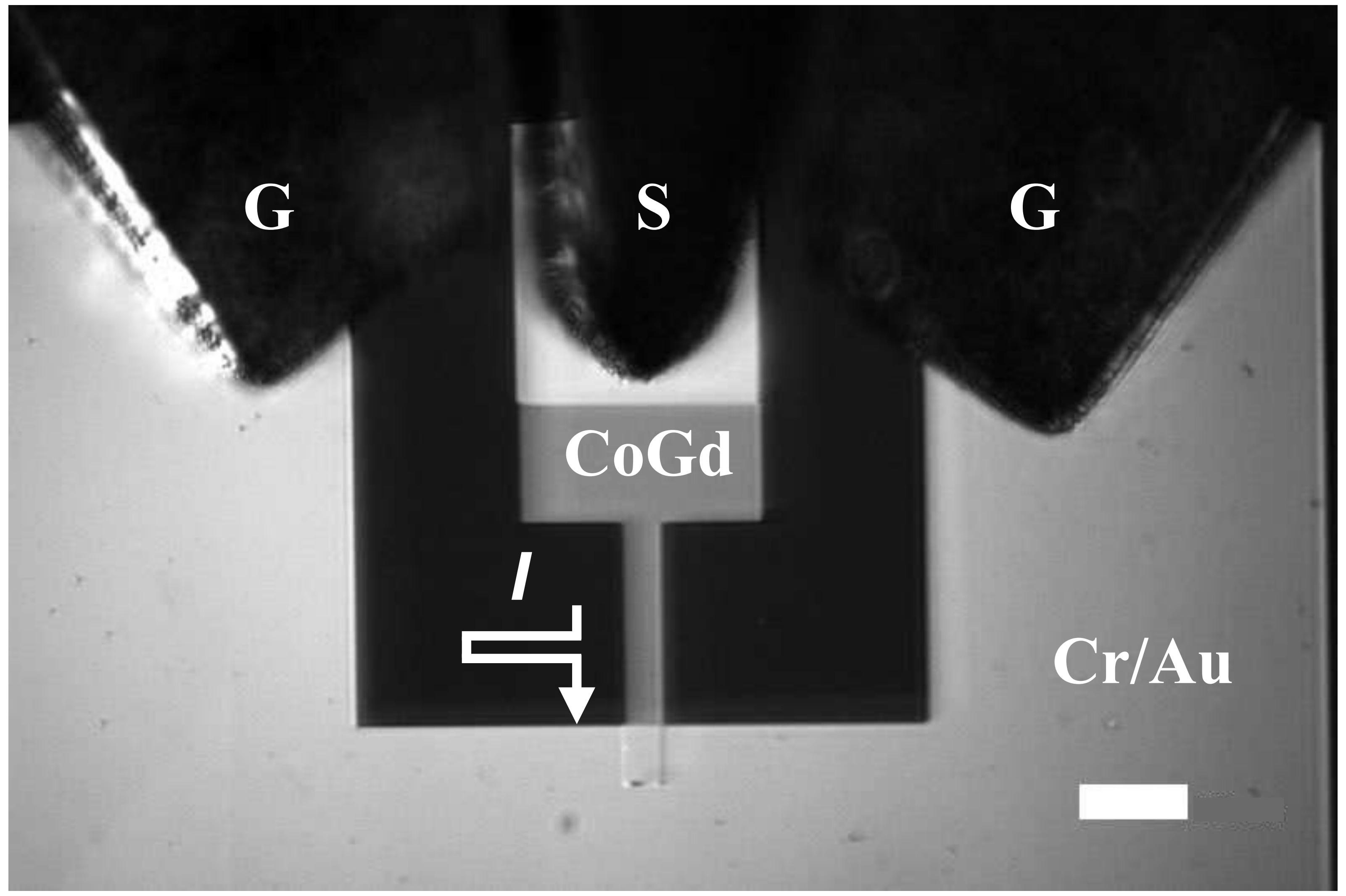
T = 300 K

Y. Quessab *et al.,* Advanced Science **8**, 2100481(2021)

Current-induced domain wall motion

- **Goal**: characterize the **SOT-induced DW dynamics in Pt/CoGd(5 nm)/(W or Ta)**
- DW motion is induced by 5-ns current pulses using a GSG probe.
- Imaging is done by a home-made polar MOKE microscope.





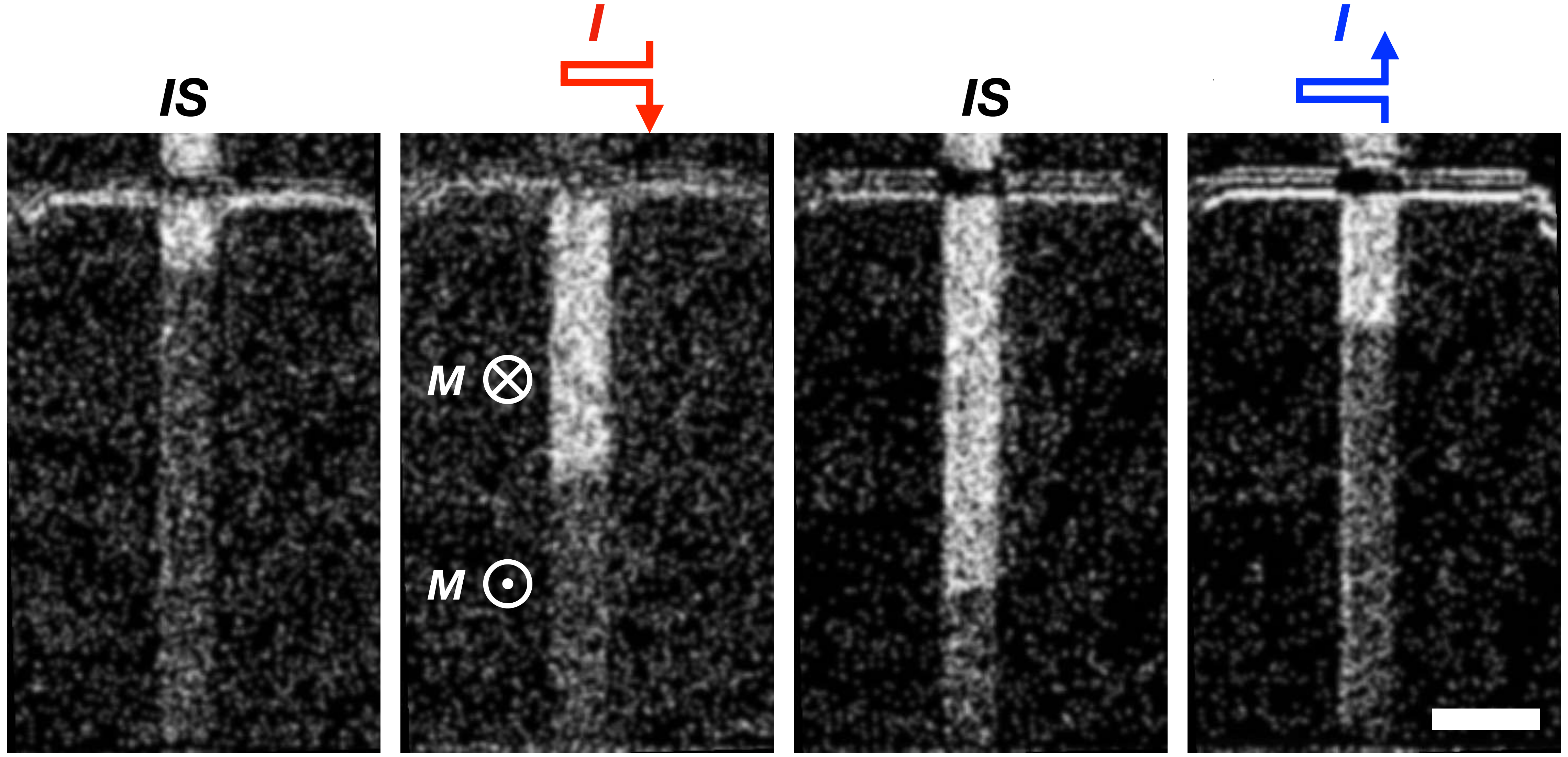
Current-induced domain wall motion

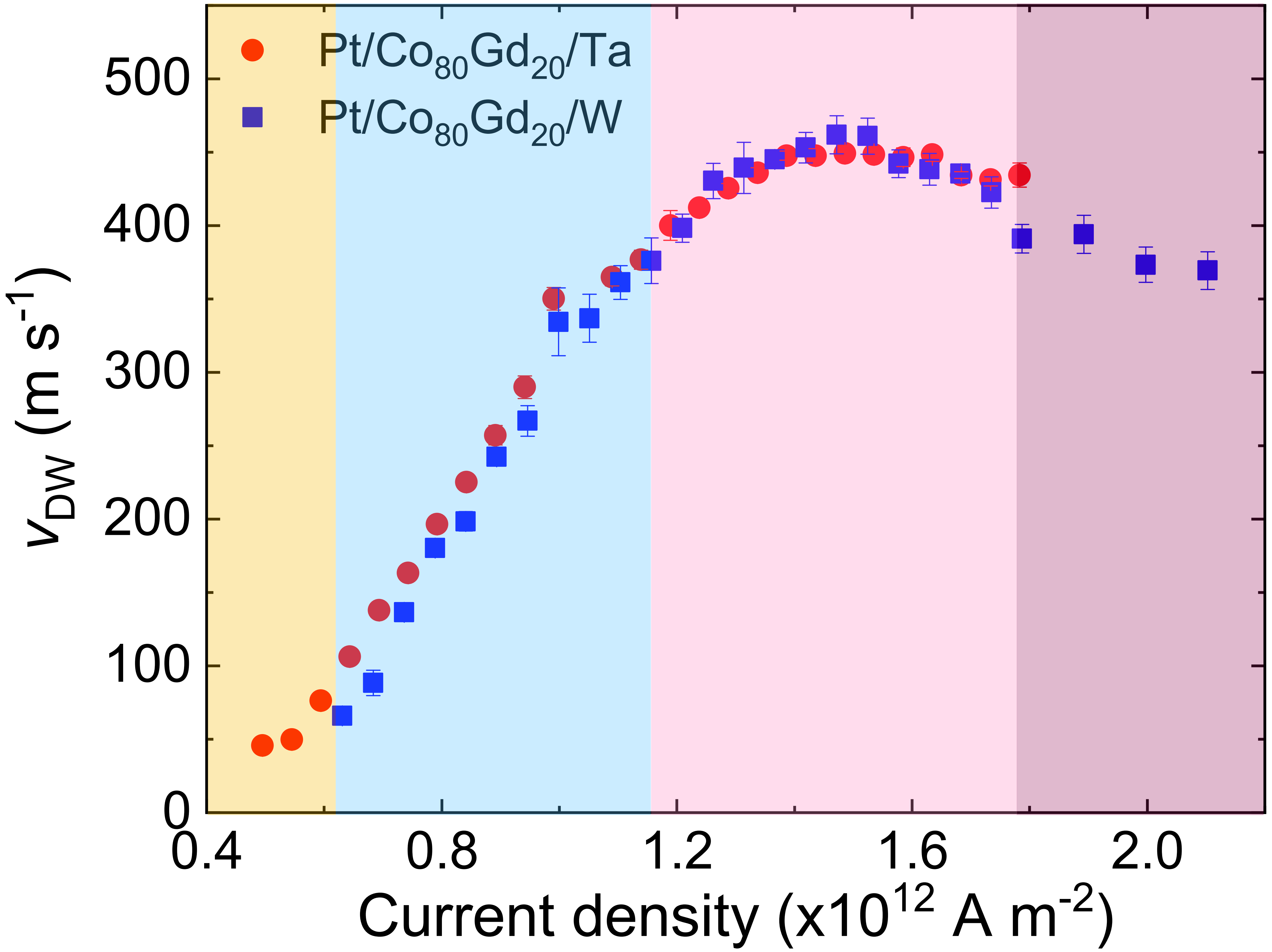
L. Caretta *et al.*, *Nat. Nano.* **13**, 1154-1160 (2018)

- DW displacement direction reverses by changing the current polartity
- Down-up and up-down DWs move in the same direction
- Consistent with SOTs-driven motion of Néel DWs.
- **$v_{\max}$(Ta) ~ 448 m/s; $v_{\max}$(W) ~ 460 m/s**

$$v_{\mathrm{DW}} = \frac{\pi}{2}\frac{Dj}{\sqrt{\left(S_{\mathrm{net}}(T)j\right)^2 + \left(\alpha S_{\mathrm{tot}} j_0\right)^2}}$$

$$\lim_{j\to\infty} v_{\mathrm{DW}}(j) = \frac{\pi}{2}\frac{D}{S_{\mathrm{net}}(T)}$$



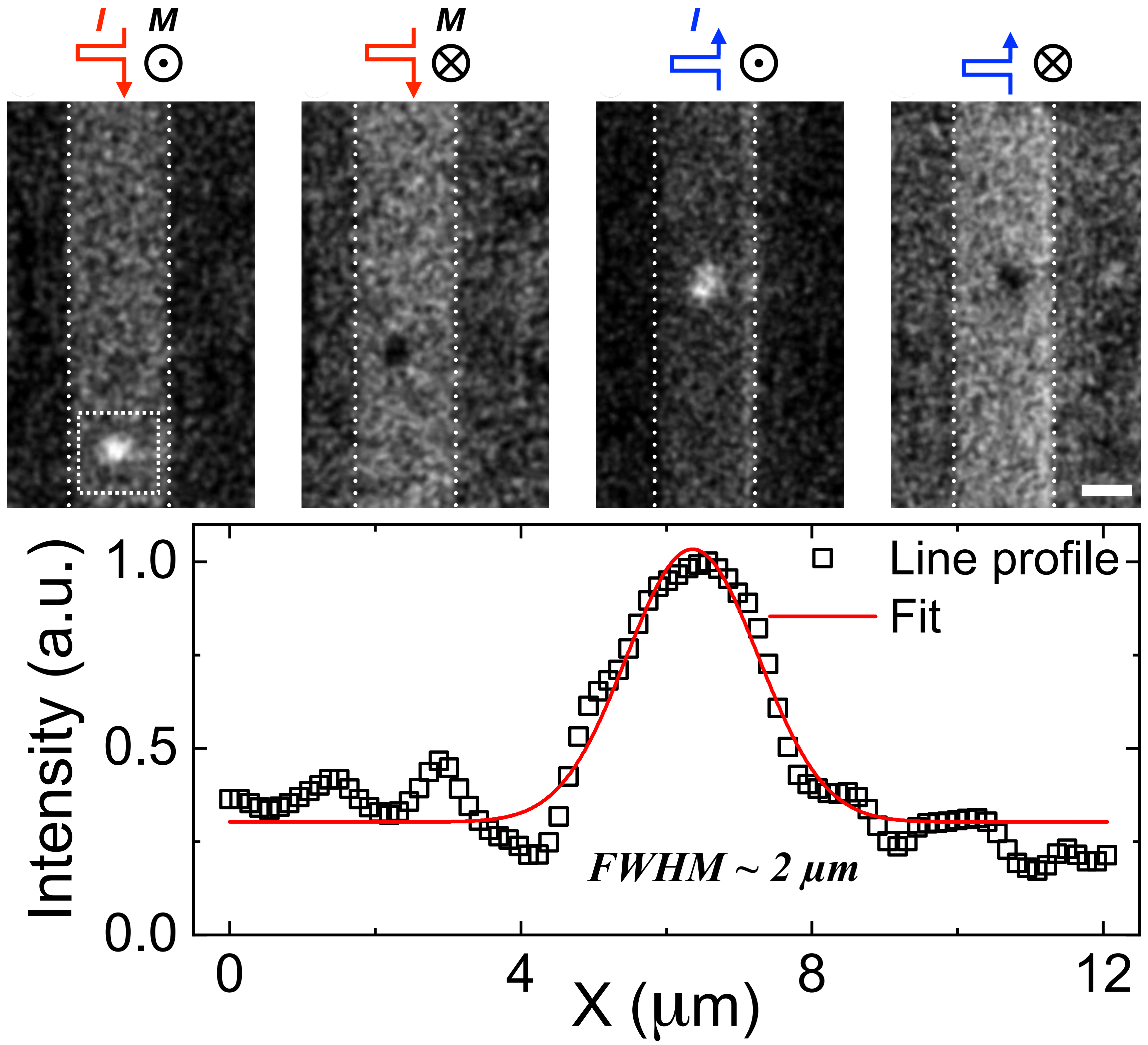


CoGd racetracks have very low DW pinning and density of natural defect $\Longrightarrow$ ideal to study SK motion

Current-induced nucleation of skyrmions

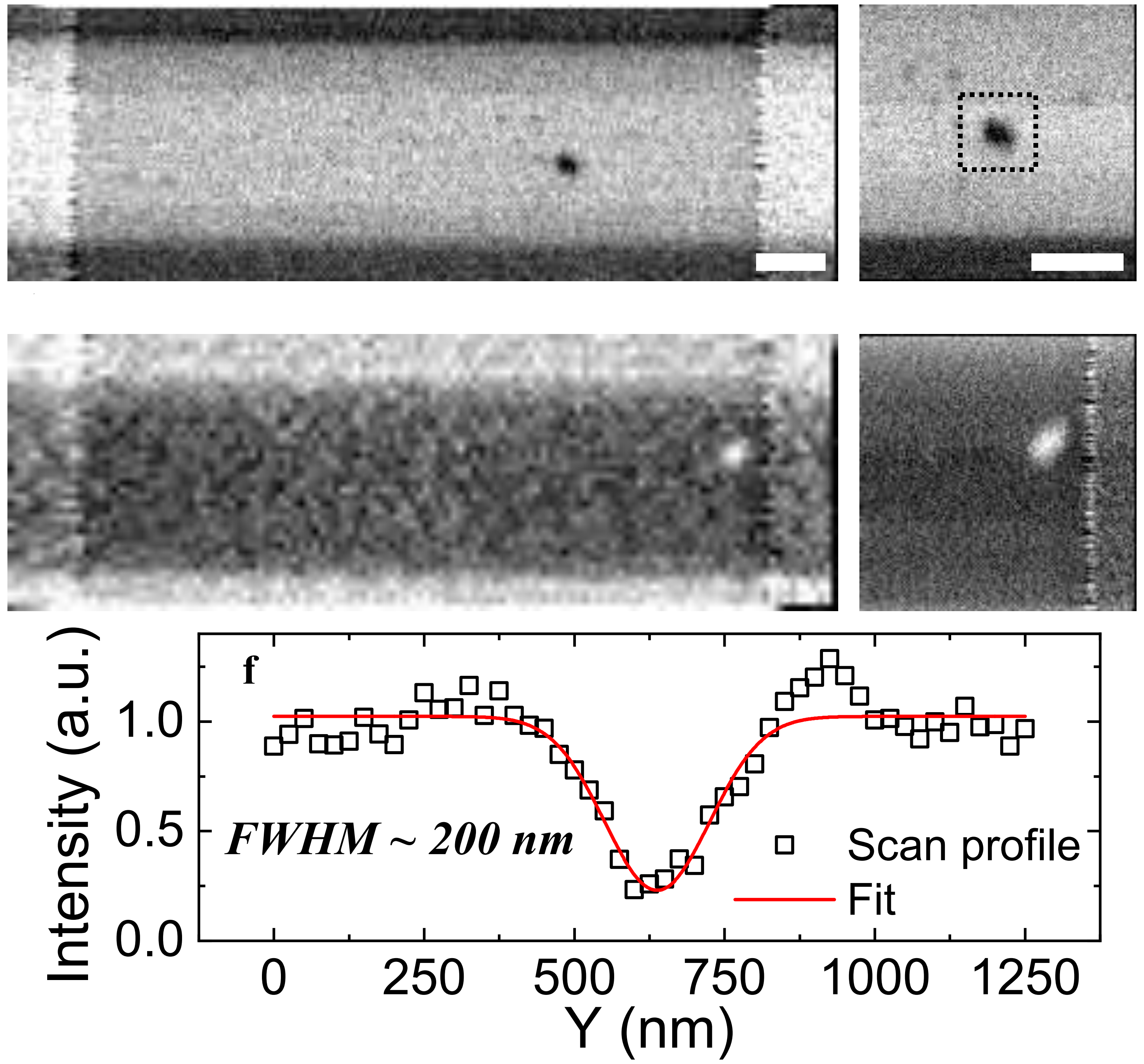
- **Observation of zero-field nucleation of SK bubbles by a single 5-ns current pulse**
- Nucleation does not depend on initial magnetization direction and current polarity ➡ ***thermal process***
- **Zero field nucleation of 200-nm skyrmion by a train of 5-ns current pulses**

Pt/CoGd(5 nm)/Ta



$\mu_0 H_z = 0$ mT; $j_x = 1.81 \times 10^{12}$ A m^{-2}

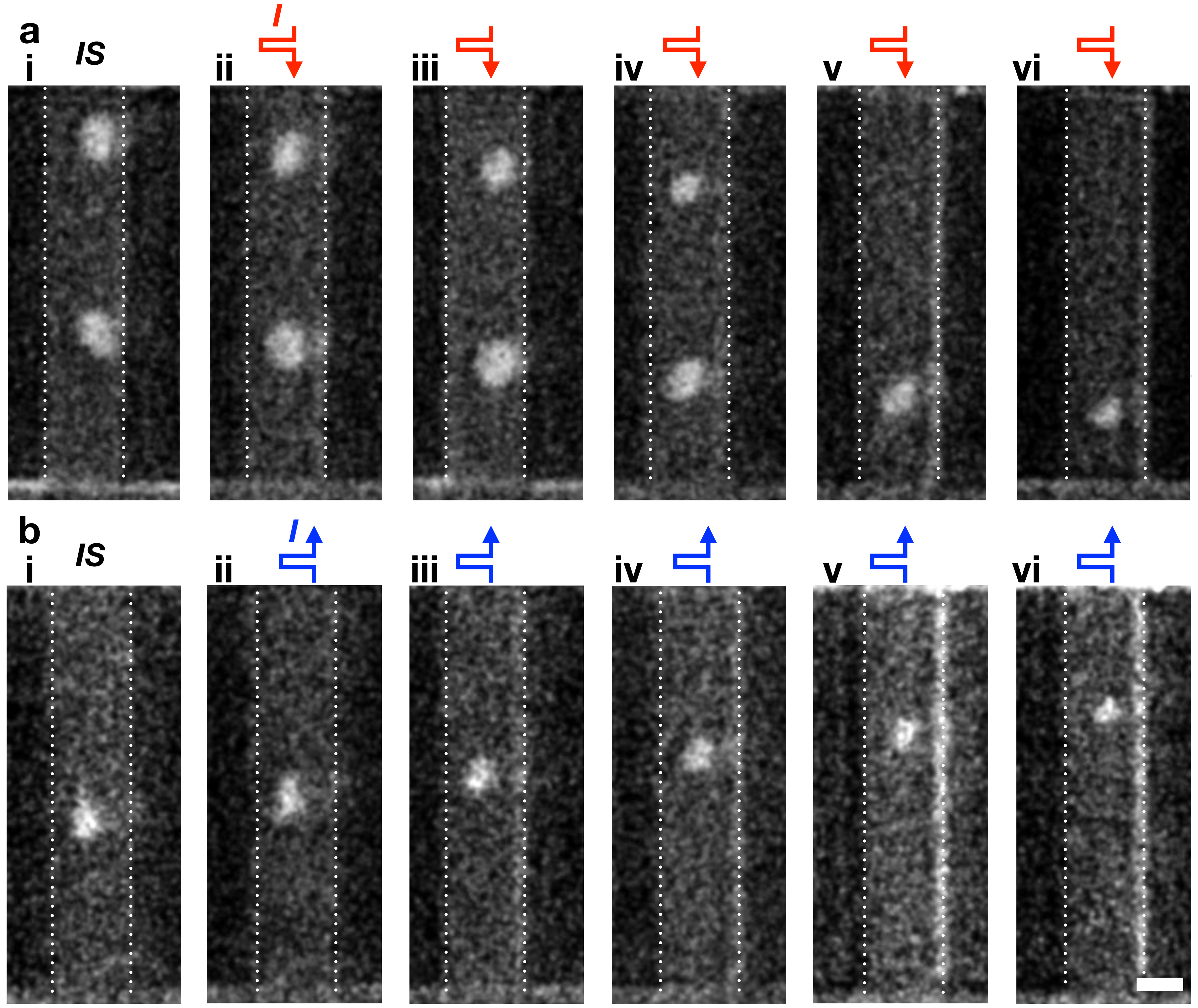
Pt/CoGd(5 nm)/W



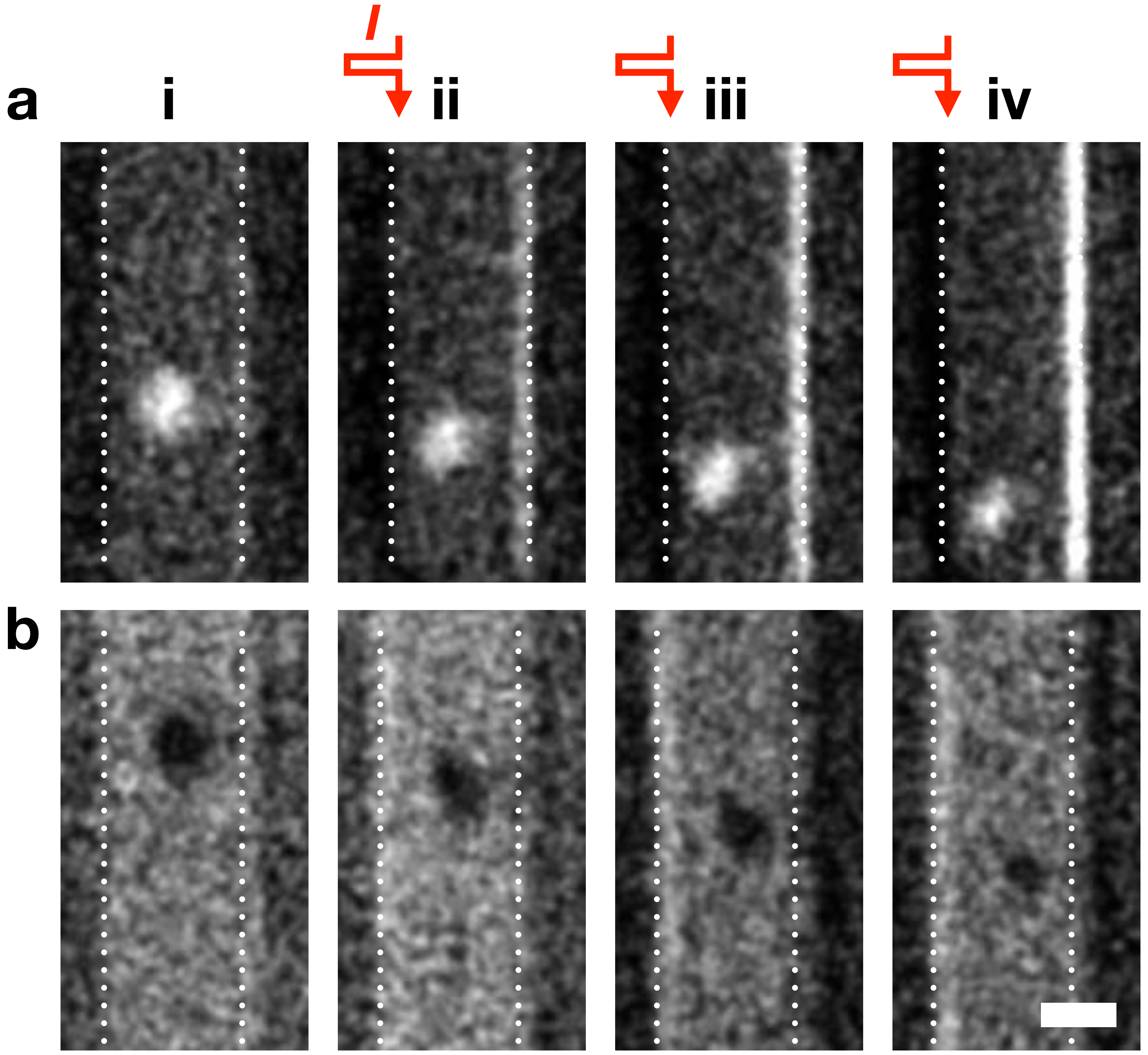
$\mu_0 H_z = 0$ mT; $j_x = 8.6 \times 10^{11}$ A m^{-2}

Current-induced skyrmion motion

- The SK displacement changes when reversing the current polarity.
- SKs with a core pointing up or down move in the same direction.
- The SK motion is indeed induced by SOTs.
- Stochastic annihilation is possible due to Joule heating.

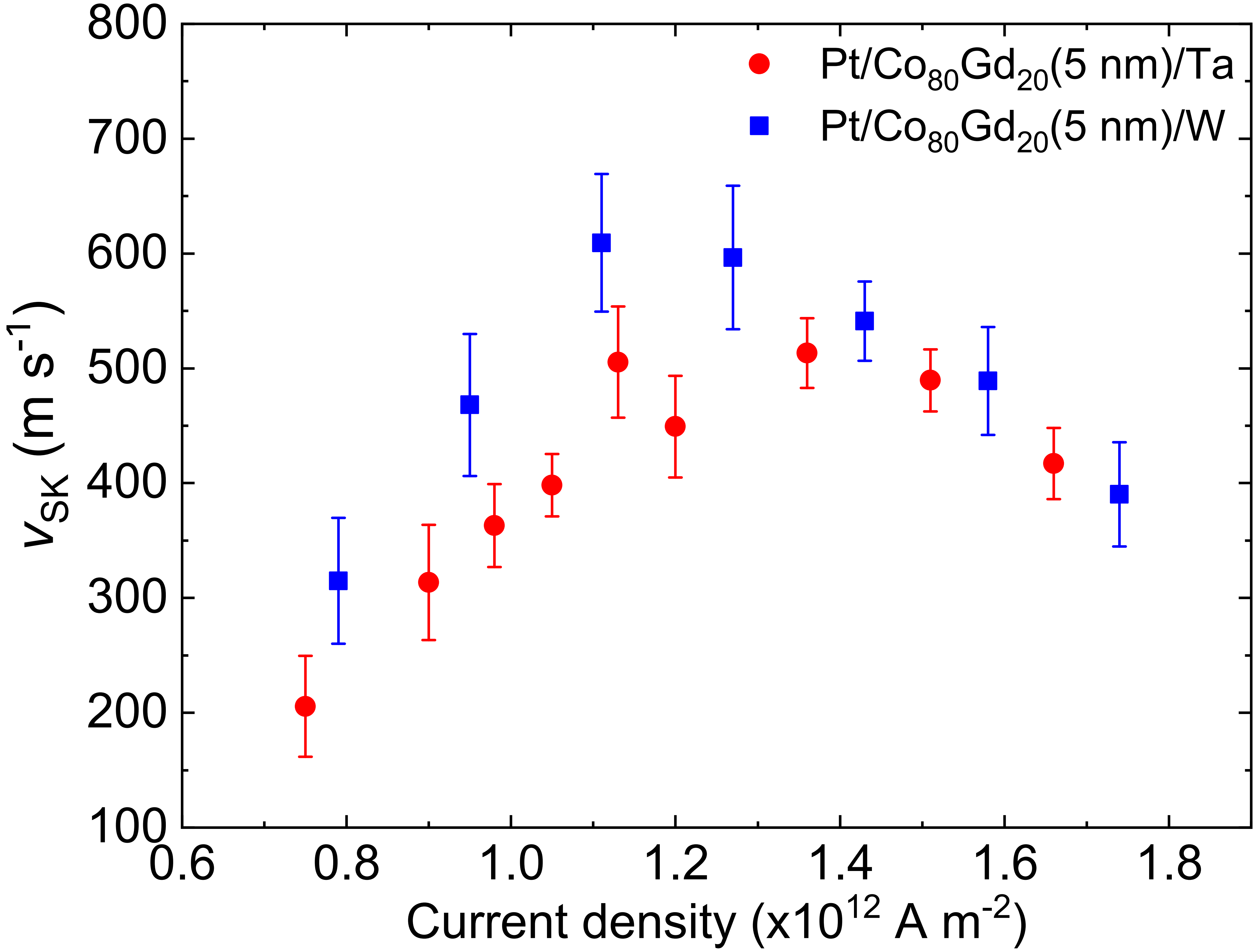


$\mu_0 H_z$ = -5.7 mT; j_x = 1.8 x 10^{12} A m^{-2}; v_{SK} ~ 400 m s^{-1}



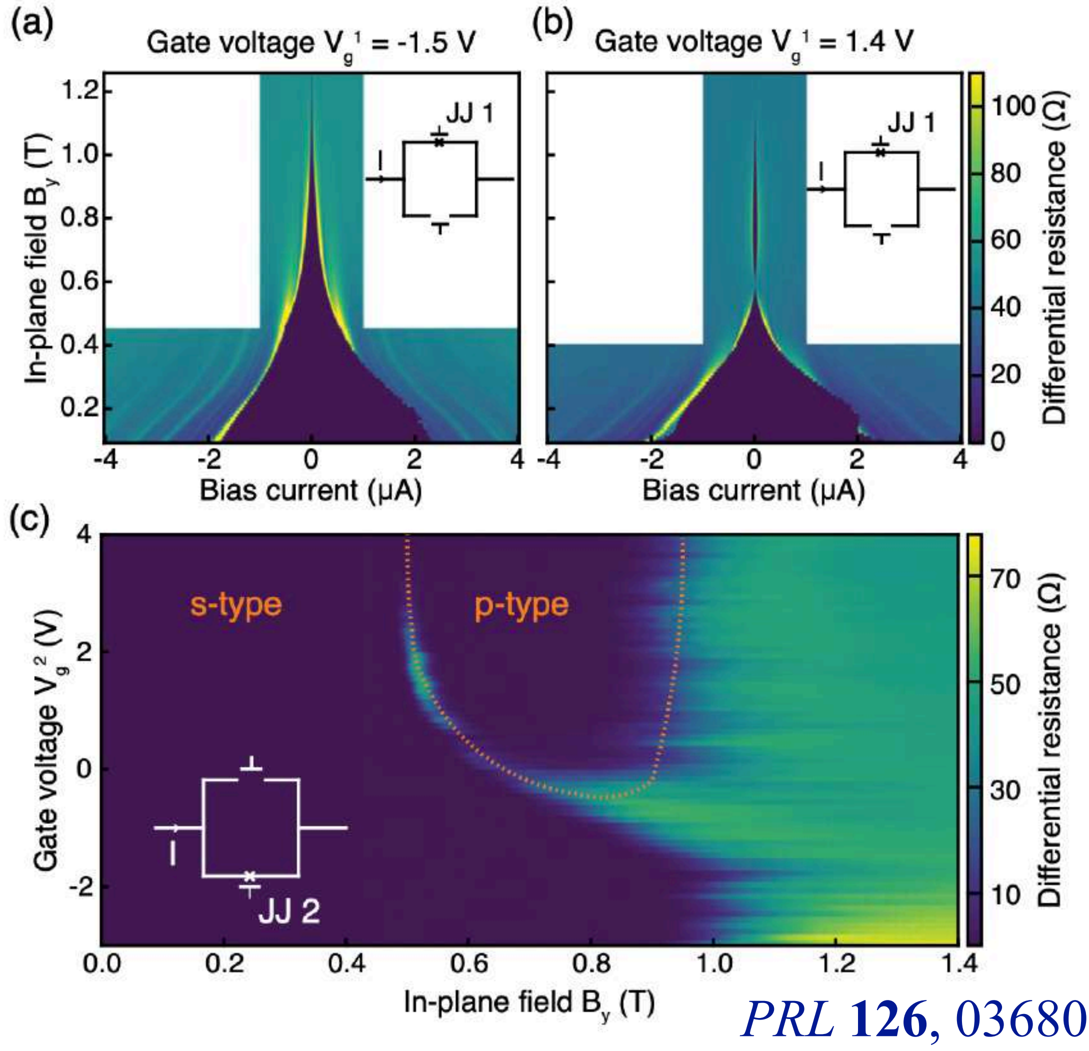
Current-induced skyrmion motion

- High mobility of SK bubbles at RT with a maximum velocity of $\boldsymbol{v_{SK}} \sim$ **610 m s^{-1}** (highest SK velocity reported thus far!)
- SKs move faster in Pt/CoGd/W than in Pt/CoGd/Ta
- Theory predicts a plateau ($\boldsymbol{S_{net} \neq 0}$) but a decrease of the SK velocity is observed at large current densities
- Deviation from the Thiele approximation, we cannot entirely consider the SK as a rigid texture.

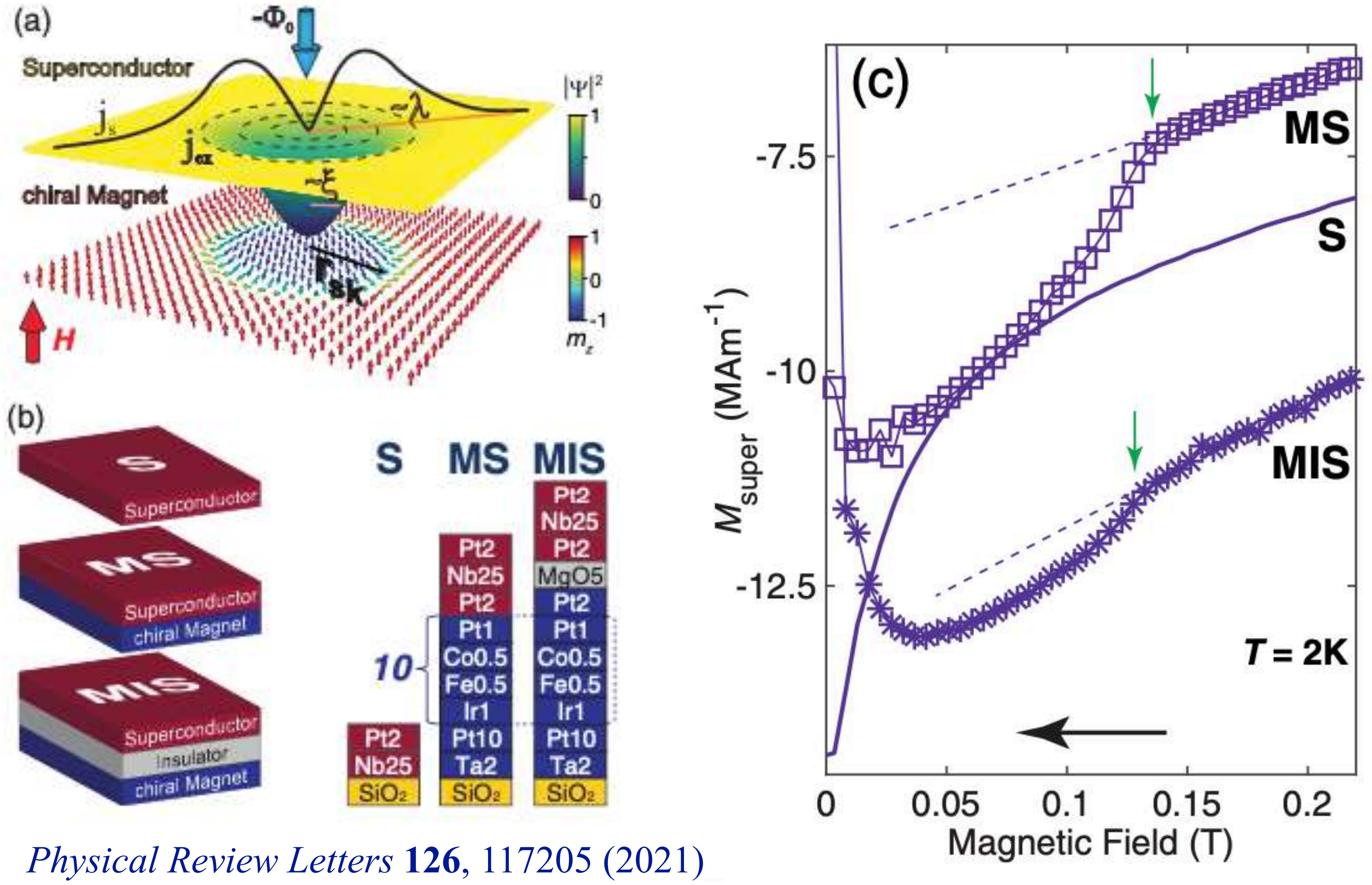


Perspective: skyrmions and quantum applications

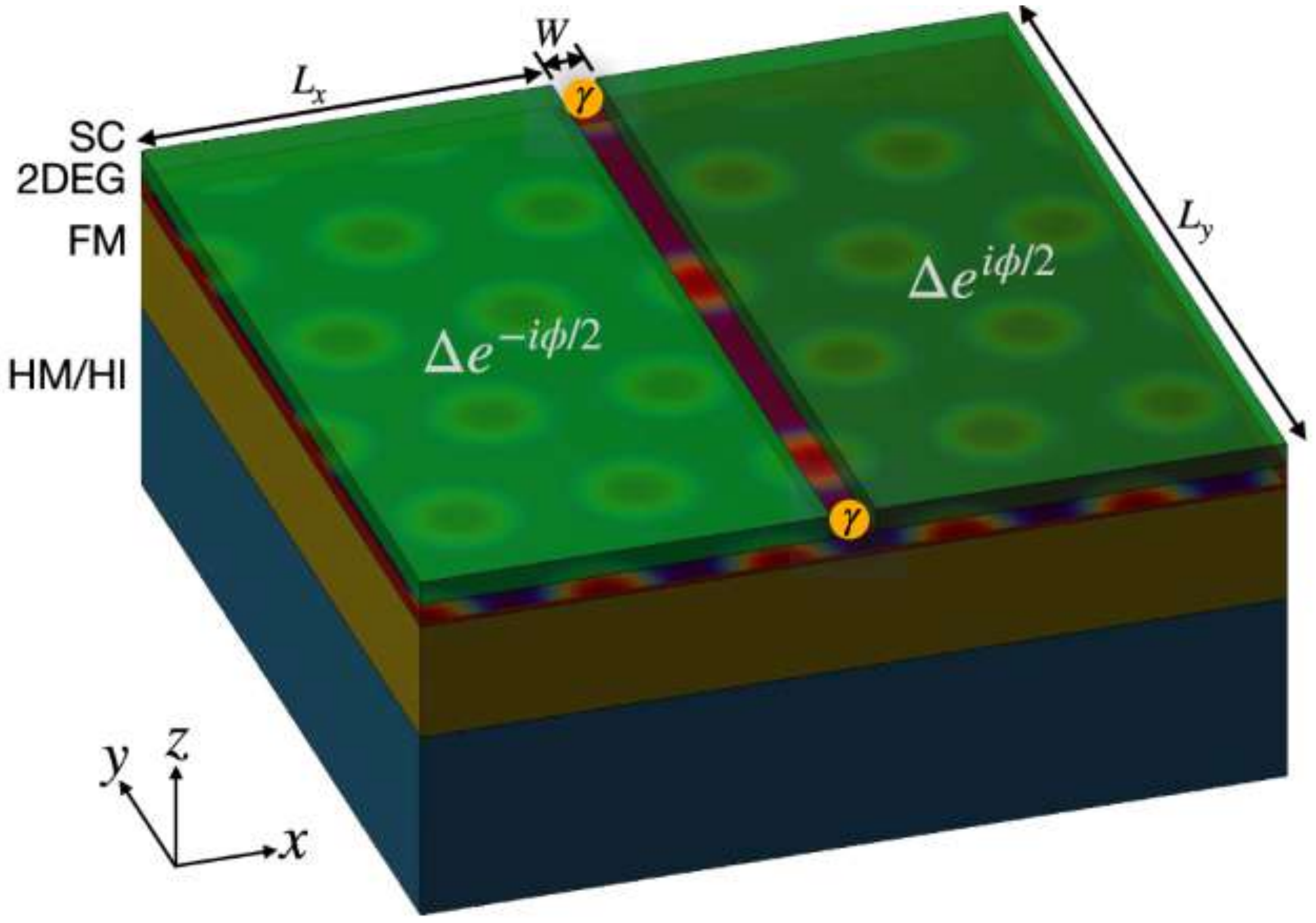
- **Skyrmions can be used to nucleate (anti)-vortices in superconductors.**
- **Can the topological phase emerge without using a global magnetic field?**
- **Spatial variation of the skyrmion stray field can create a spatial-dependent SOC that can enable Majorana Fermions**
    - Growth of ferromagnet on top of a semiconductor/superconductor heterostructure that exhibits a topological phase



PRL **126**, 036802 (2021)

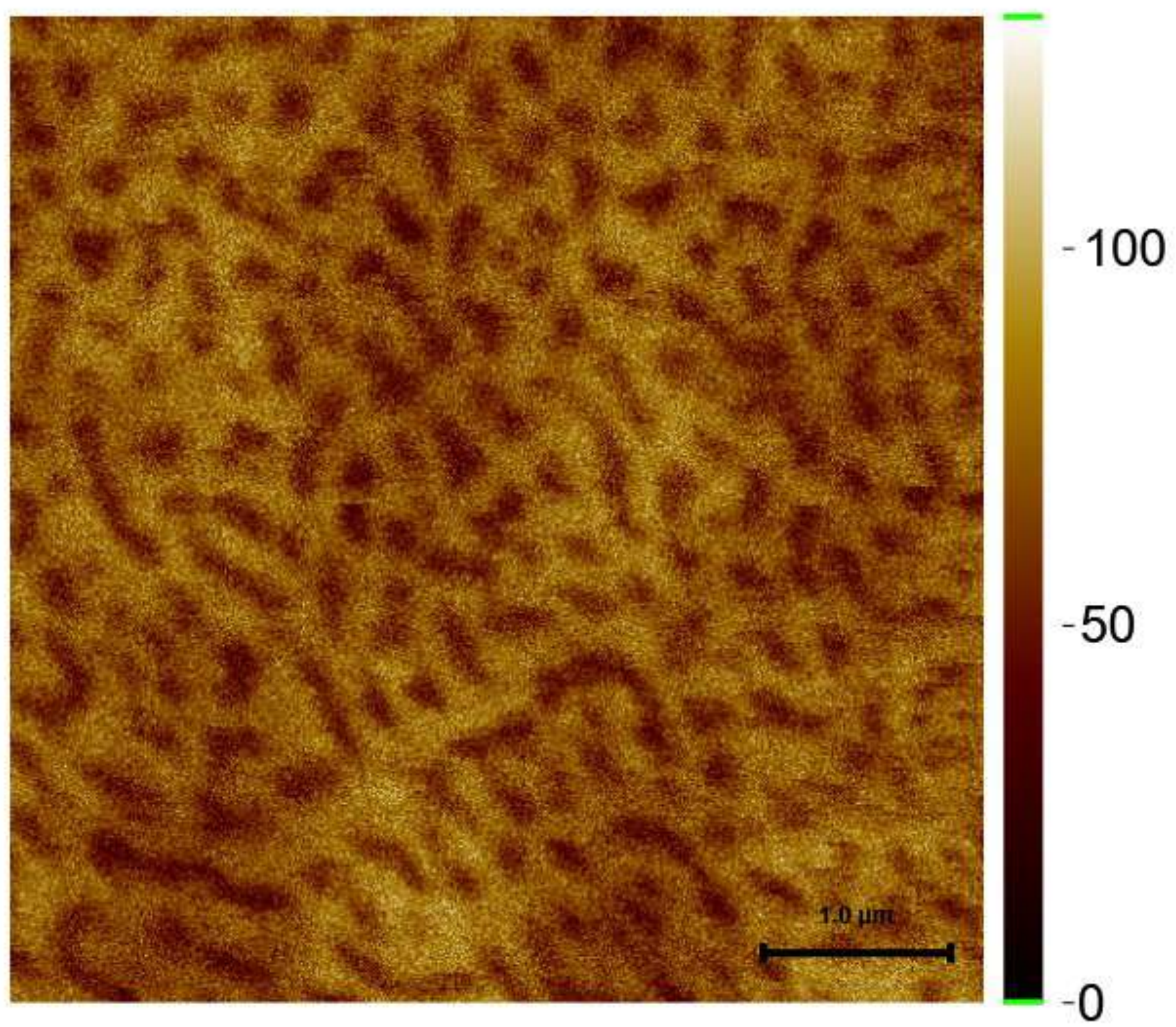


Physical Review Letters **126**, 117205 (2021)



Communication Physics **4**, 163 (2021)

MFM

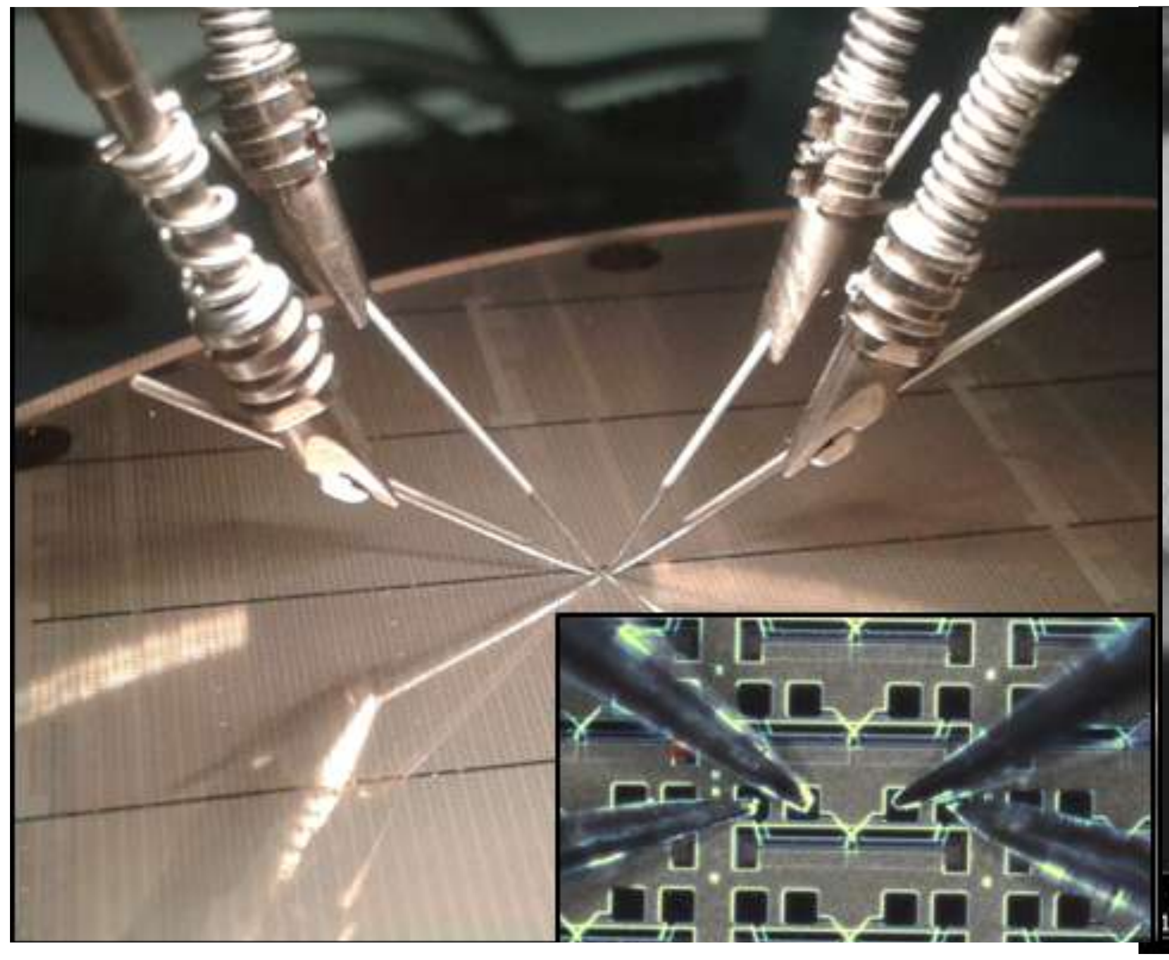


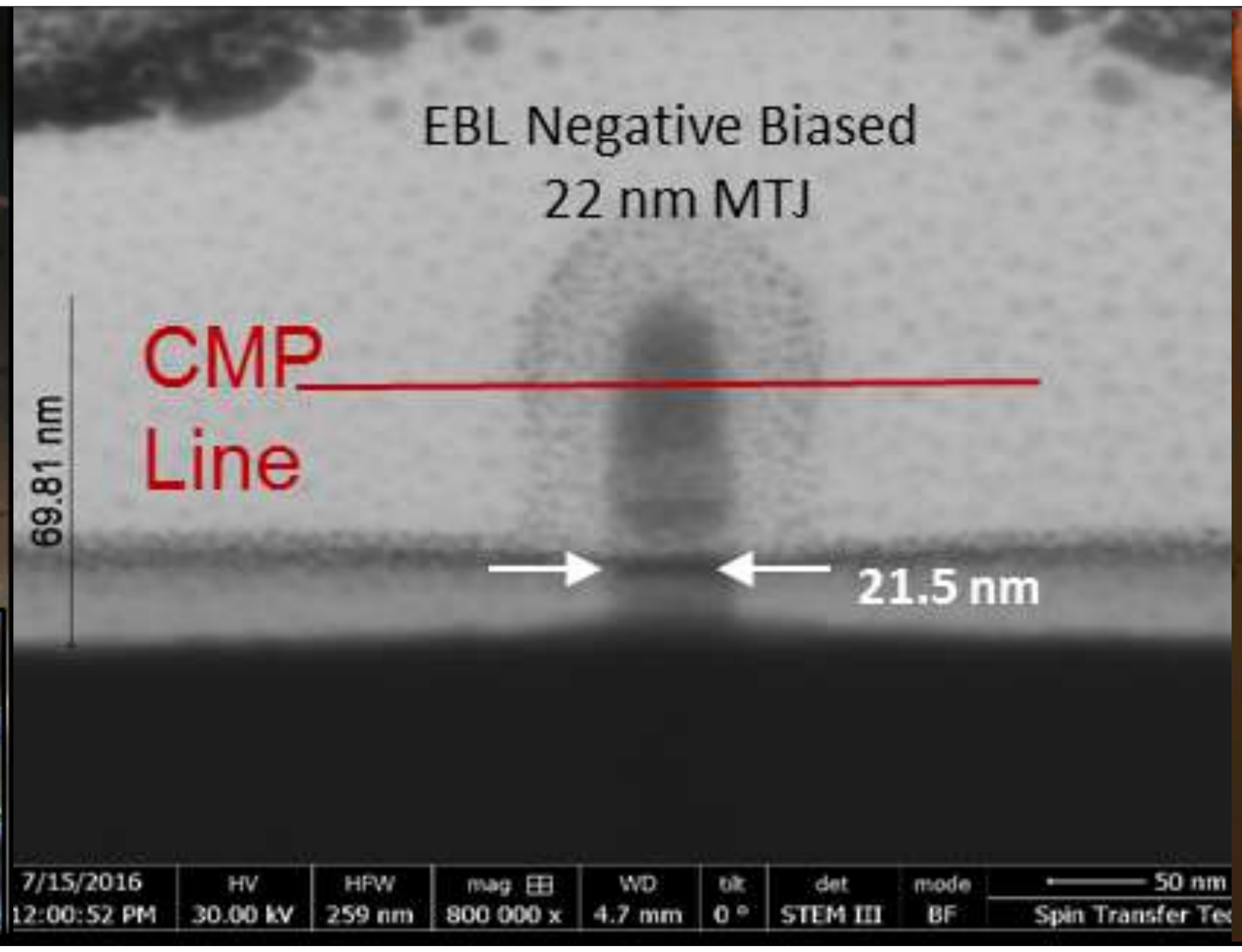
InAs/Al/(hBN)/[Pt/Co/X]$_N$

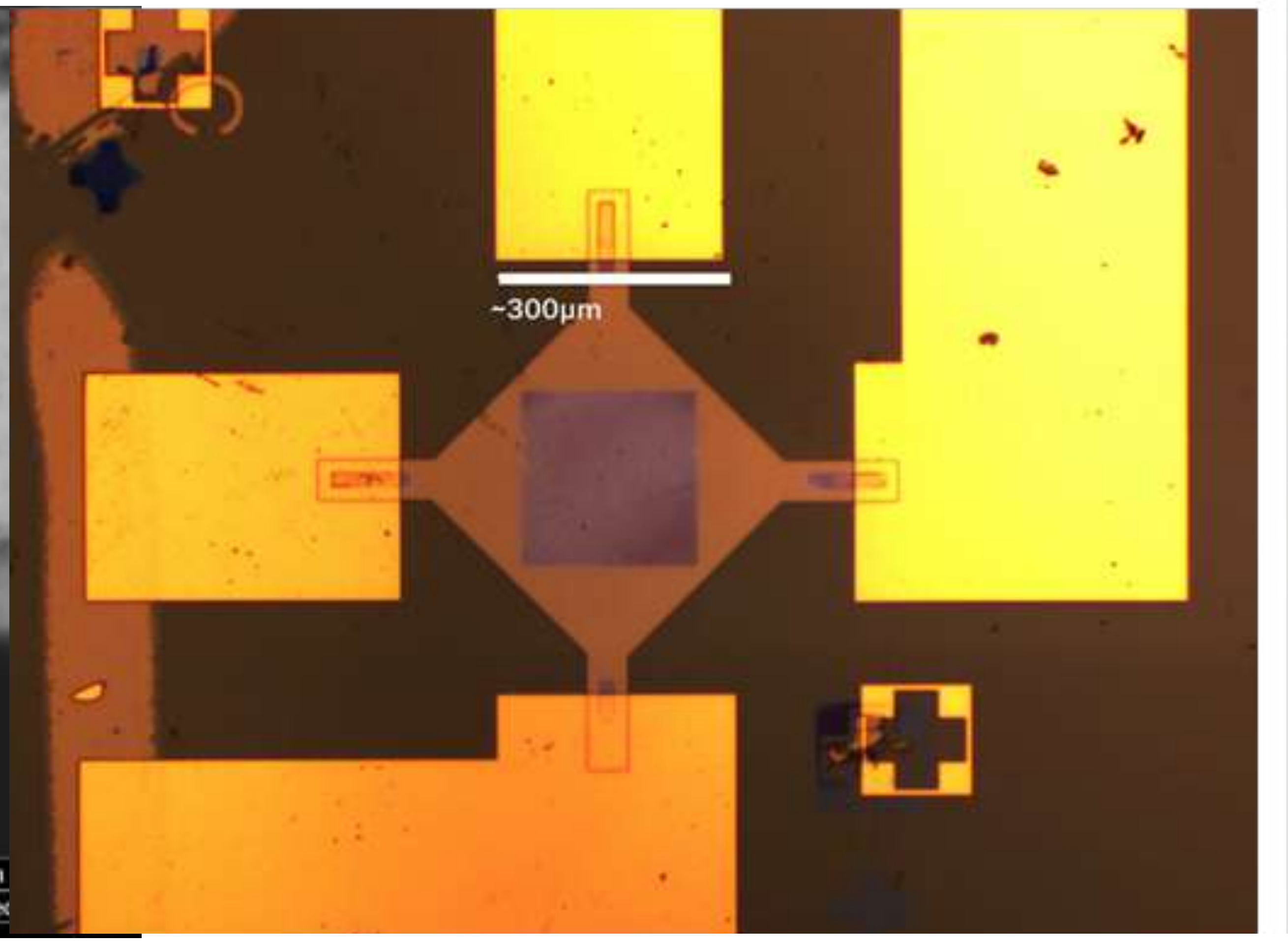
NYU

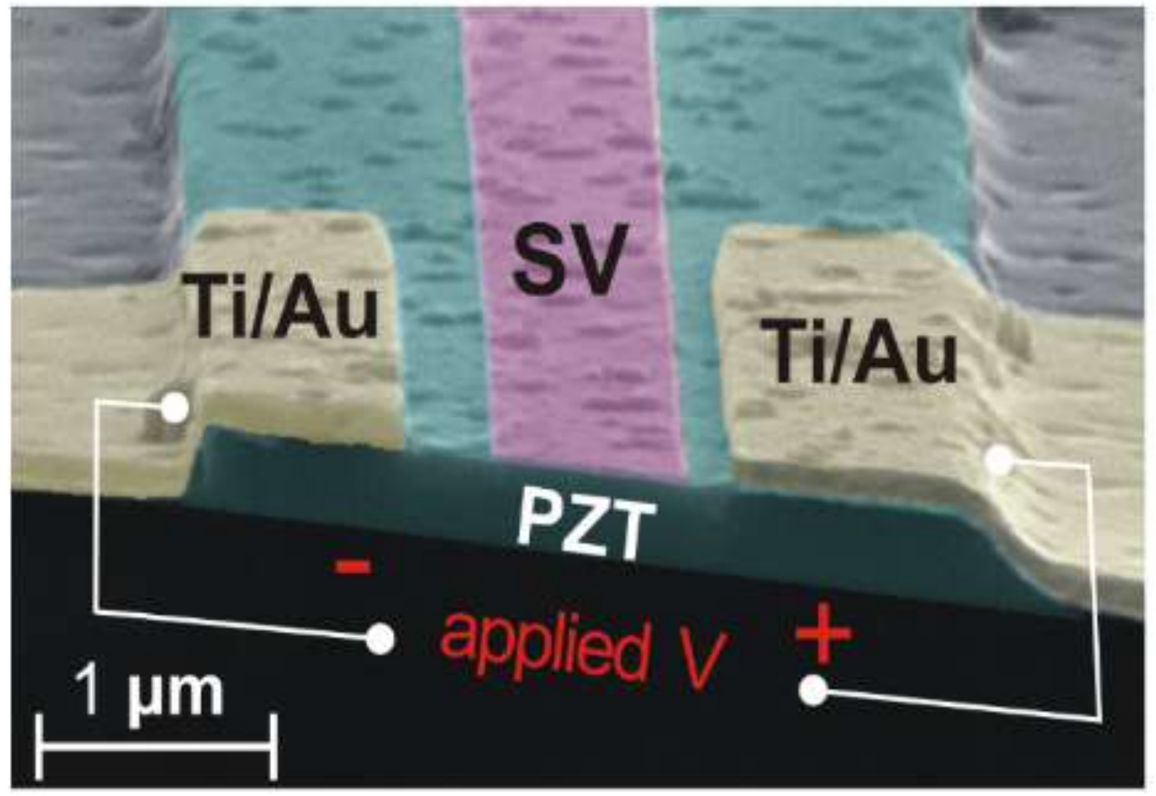
New Magnetic Nanotechnologies

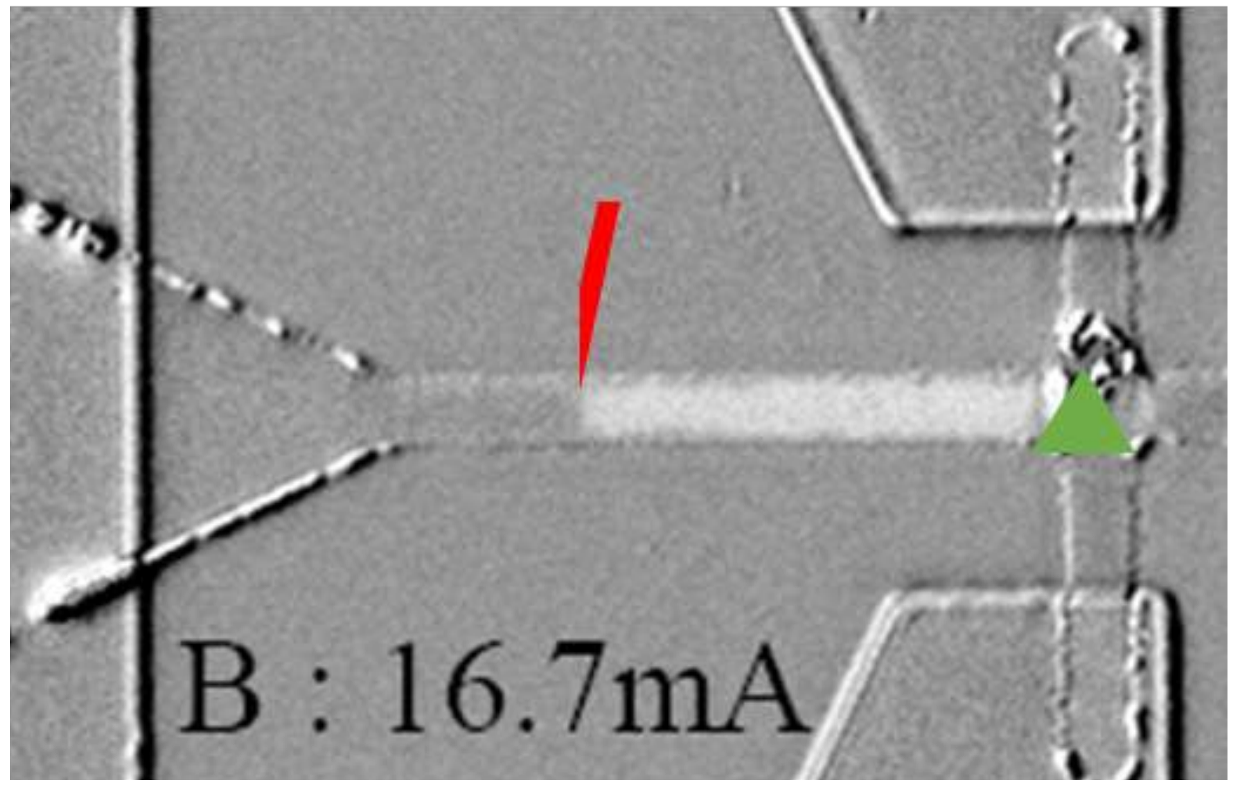
Nanoelectronics, from new phenomena to low power electronics

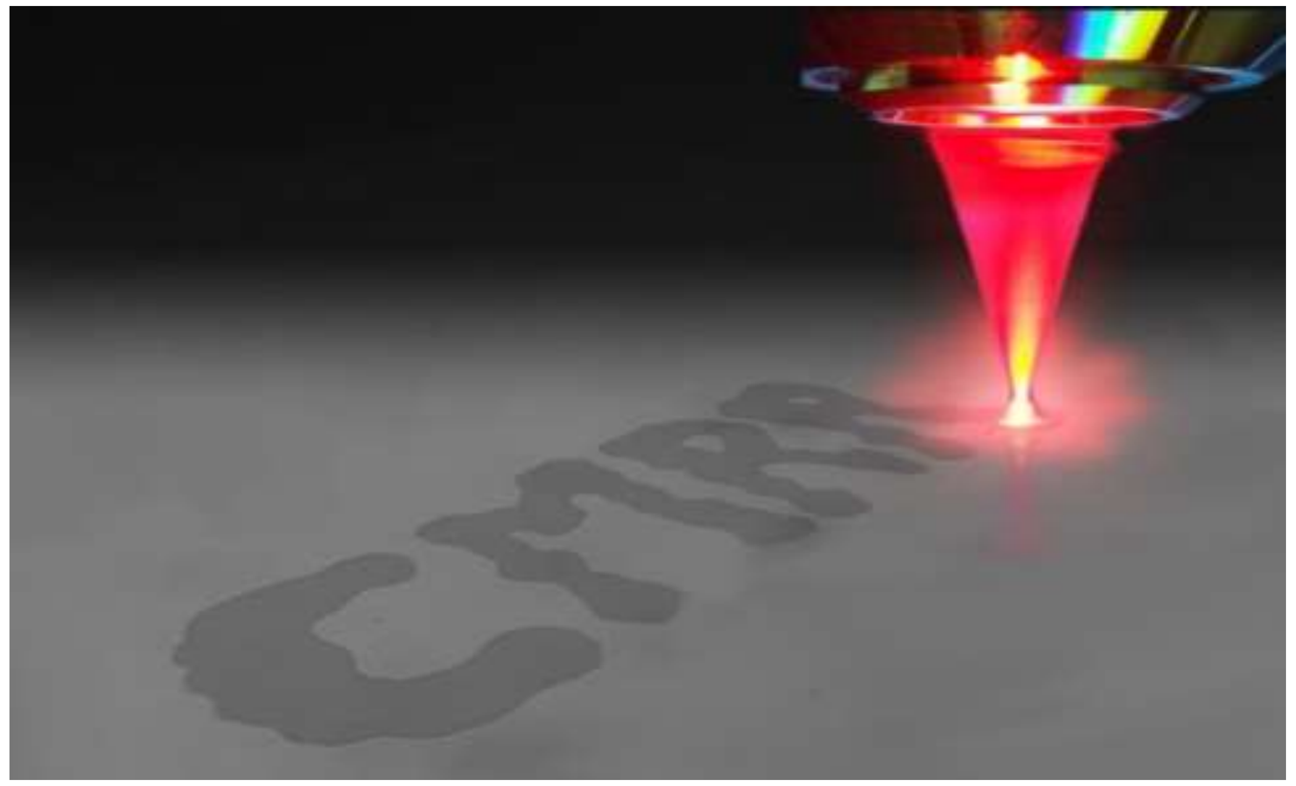












International Associated Laboratory (LIA)

UCSD
UNIVERSITÉ DE LORRAINE
université PARIS-SACLAY
NYU

A New Spin on Magnetism with Applications in Information Processing

Outline

- Spintronics and spin-transfer torques
- Switching magnetization in magnetic tunnel junction nanopillars
- Magnetic skyrmions
- **Center for Quantum Phenomena NYU NY**

NYU Center for Quantum Phenomena

Paul Chaikin - CMP Experiment
Andy Kent - CMP Experiment
Aditi Mitra - Theory
Dries Sels - Theory
Davood Shahrjerdi - ECE Experiment
Dan Stein - Theory
Andrew Wray - CMP Experiment

NYU AD: Center for Quantum and Topological Systems

NYU

NYU Center for Quantum Phenomena

- **Quantum Materials and Devices**
- **Out-of-Equilibrium Quantum Systems**
- **Quantum Information**

- CQP inauguration: June 2017
- Official opening: September 1, 2017
- Laboratory space dedicated to CQP and new facilities

Center has 9 physics faculty, with associated faculty in **Engineering**

- There is a search this academic year for two QCMP/AMO experimental physicists
- There are ties to faculty at NYU Shanghai
- There are affiliated faculty in the NYU Tandon School of Engineering

A New Spin on Magnetism with Applications in Information Processing

Summary

- Spintronics and spin-transfer torques
- Switching magnetization in magnetic tunnel junction nanopillars
- Magnetic skyrmions
- Center for Quantum Phenomena NYU NY

Acknowledgments

NYU Team: Dirk Backes*, Corrado Capriata, 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*, Nahuel Statuto, 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 & Chris Safranski
-NYU: Gabriel Chaves and Dan Stein
-University of Barcelona and ICMAB-CSIC: Nahuel Statuto & Ferran Macia
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-BBN Raytheon: Tom Ohki, Colm Ryan & Graham Rolands
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-Sandia National Lab: Shashank. Misra, J. Darby Smith, J. Brad Aimone
-KTH, Sweden: B. Gunnar Malm
-University of Lorraine: Carlos Rojaz Sanchez, Stephane Mangin & Sebastien Petit-Watelot
-U. Paris Saclay, C2N: Dafine Ravelosona
-UCSD: Eric Fullerton
-WD-HGST: Jordan Katine