Spin Transfer Torque

by Aurélien Manchon
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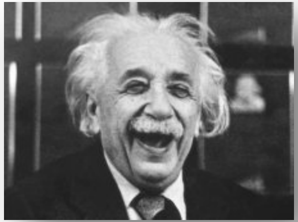
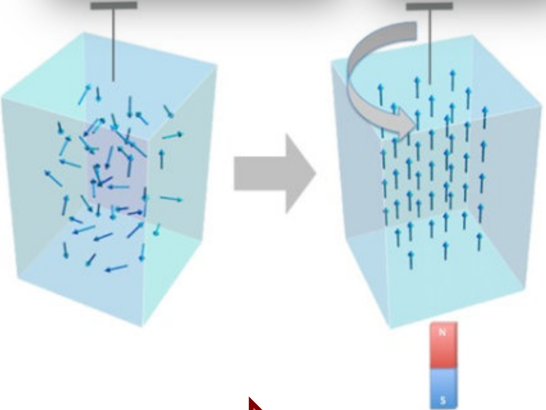
The art of throwing spinning balls

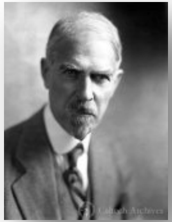
Einstein de Haas effect

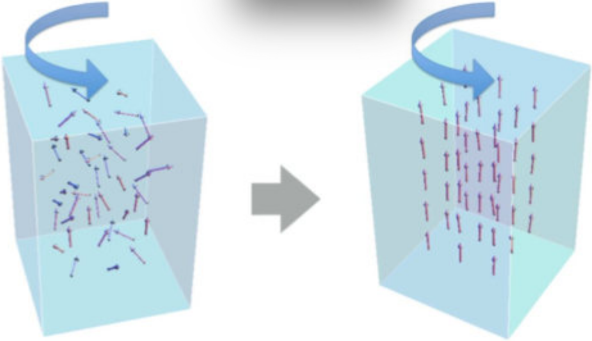




Magnetic field ⇨ Mechanical torque

Barnett effect





Mechanical Torque ⇨ Magnetization

For more information

Matsuo, Mechanical generation of spin current, Frontiers in Physics 3, 54 (2015)

Also Comment by Kovalev, Nature Nanotechnology 3, 710 – 711 (2008).

The art of throwing spinning balls

Slonczewski's picture: angular momentum conservation

$$\boldsymbol{M} - g\mu_B \boldsymbol{s} = \text{constant}$$

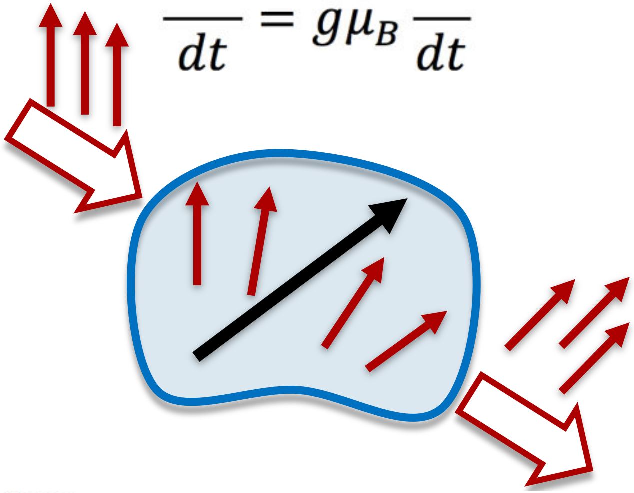
"Local" magnetization — "conduction" spin

$$\frac{d\boldsymbol{M}}{dt} = g\mu_B \frac{d\boldsymbol{s}}{dt}$$

L. Berger

J. Slonczewski

The torque exerted by the conduction spins on the magnetization is given by the balance between incoming and outgoing spin current



Spin current *transverse* to **M**

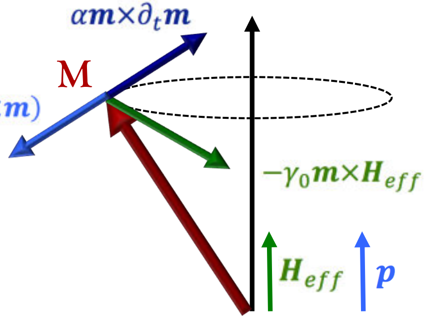
$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{T} = \int d\Omega \boldsymbol{m}\times[(\boldsymbol{J}_s^{in} - \boldsymbol{J}_s^{out})\times\boldsymbol{m}]$$

J. C. Slonczewski, Journal of Magnetism and Magnetic Materials 159, L1 (1996)

The art of throwing spinning balls

Current-driven dynamics

$$\partial_t \boldsymbol{m} = -\gamma_0 \boldsymbol{m}\times\boldsymbol{H}_{eff} + \alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} + \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$$

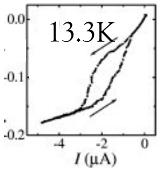


$\alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} > \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ M relaxes towards H_{eff}

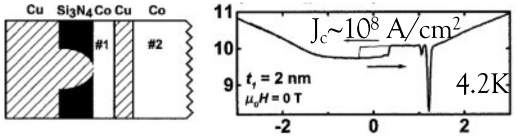
$\alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} < \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ M switches towards $-H_{eff}$

$\alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} = \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ M precesses about H_{eff}

$La_{0.67}Sr_{0.33}MnO/SrTiO_3$
$A\sim170\times170$ A^2, $J_c\sim10^5$ A/cm^2
Thermally activated switching



Sun, Journal of Magnetism and Magnetic Materials 202, 157 (1999)



Myers, Science 285, 867 (1999)

I. Spin Transfer Torque

II. Current-driven dynamics

III. Domain walls and skyrmions

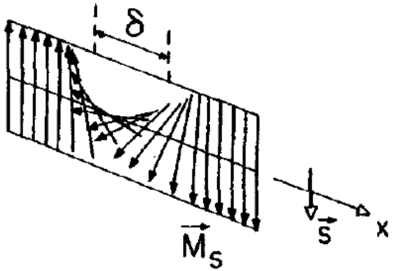
I. Spin Transfer Torque and Spin Pumping

a. Transfer of angular momentum

b. Spin pumping

Principle of spin transfer torque

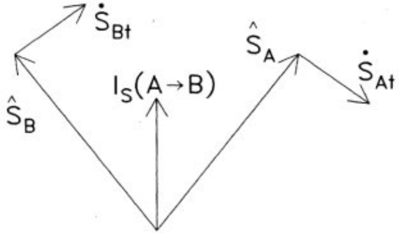
Spin torque in magnetic domain walls



“As an electron crosses the wall, its spin s follows closely the direction of [...] the local magnetization $\mathbf{M}_s$.”

Berger, Journal of Applied Physics 49, 2156 (1978)
Berger, Journal of Applied Physics 55, 1954 (1984)

Spin torque in magnetic tunnel junctions



“Since S_A-polarized electrons impinge on magnet B, surely S_B must relax toward

$$J_s \sim S_A + S_B$$

$$\partial_t S \partial_t S_A = -S_A \times (J_s \times S_A)'_A]$$

$$\partial_t S_A \propto S_A \times (S_A \times S_B)$$

Slonczewski, Physical Review B39, 6995 (1989)

Principle of spin transfer torque

The spin continuity equation

Insight from s-d model

s-d exchange between localized and itinerant spins

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_d + \hat{\mathcal{H}}_s - \Delta \sum_i \hat{\boldsymbol{S}}_i \cdot \hat{\boldsymbol{\sigma}}$$

"Itinerant" spins

Local moments

rg exchange, anisotropy etc.

Kinetic energy

Crystal potential

Spin-orbit coupling etc.

Ehrenfest's theorem

$$\frac{d\langle \hat{A} \rangle}{dt} = \langle \frac{\partial \hat{A}}{\partial t} \rangle + \frac{1}{i\hbar} \langle [\hat{A}, \hat{\mathcal{H}}] \rangle$$

$$\partial_t \langle \hat{\boldsymbol{\sigma}} \rangle = -\boldsymbol{\nabla} \cdot \langle \frac{1}{2m} \{\hat{\boldsymbol{\sigma}}, \hat{\boldsymbol{p}}\} \rangle + \frac{2\Delta}{\hbar} \langle \hat{\boldsymbol{\sigma}} \times \hat{\boldsymbol{S}}_i \rangle$$

$$\partial_t \langle \hat{\boldsymbol{S}}_i \rangle = \frac{g\mu_B}{\hbar} \langle \hat{\boldsymbol{S}}_i \rangle \times \boldsymbol{B} - \frac{2\Delta}{\hbar} \langle \hat{\boldsymbol{\sigma}} \times \hat{\boldsymbol{S}}_i \rangle$$

Source of nonequilibrium spin density

"particle" spin density / Spin density

$$\boldsymbol{s} = \frac{1}{\Omega} \langle \hat{\boldsymbol{\sigma}} \rangle$$

$$\partial_t \boldsymbol{s} = -\boldsymbol{\nabla} \cdot \boldsymbol{J}_s - \frac{1}{\tau_\Delta} \boldsymbol{s} \times \boldsymbol{m}$$

Reduced Magnetization

$$\boldsymbol{m} = \boldsymbol{M}/M_s$$

$$\partial_t \boldsymbol{m} = -|\gamma| \boldsymbol{m} \times \boldsymbol{B} + \frac{1}{\tau_\Delta} \int d\Omega \boldsymbol{s} \times \boldsymbol{m}$$

Spin precession time

$$\frac{1}{\tau_\Delta} = \frac{2\Delta S}{\hbar}$$

Spin transfer torque

$$\boldsymbol{T} = \frac{1}{\tau_\Delta} \int d\Omega \boldsymbol{s} \times \boldsymbol{m} = -\boldsymbol{m} \times \left(\int d\Omega [\boldsymbol{\nabla} \cdot \boldsymbol{J}_s] \times \boldsymbol{m} \right)$$

(in units of s^{-1})

Spin dephasing and spin current absorption (Tutorial)

Quantum mechanical model

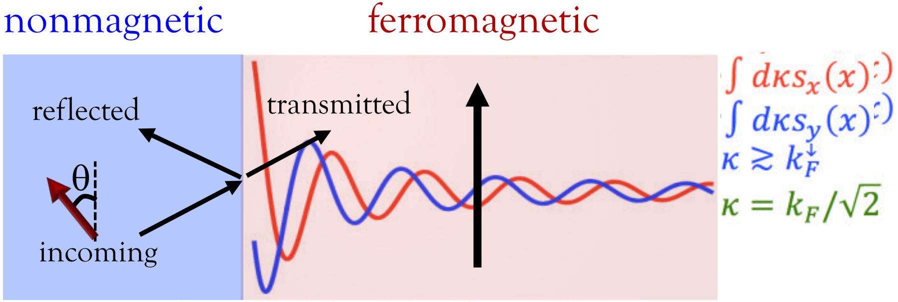
Wave function for a given spin σ

$$\psi_\sigma^N = [e^{ik_x x} + r_\sigma e^{-ik_x x}]e^{i\boldsymbol{\kappa}\cdot\boldsymbol{\rho}}$$

$$\psi_\sigma^F = t_\sigma e^{i(k_x^\sigma x + \boldsymbol{\kappa}\cdot\boldsymbol{\rho})}$$

Incoming electron with a given spin direction in (x,z) plane

$$\psi = \cos\frac{\theta}{2}\psi_\uparrow^N|\uparrow\rangle + \sin\frac{\theta}{2}\psi_\downarrow^N|\downarrow\rangle$$



$k_F = 1\,, k_F^\uparrow = 1.09, k_F^\downarrow = 0.42$ A

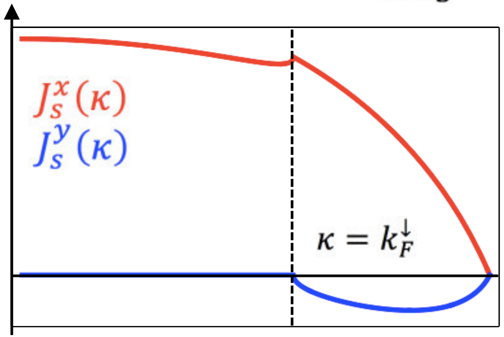
$$\boldsymbol{T} = -\boldsymbol{m}\times\left(\int d\Omega[\boldsymbol{\nabla}\cdot\boldsymbol{J}_s]\times\boldsymbol{m}\right) = \frac{\mu_B}{dM_s}\boldsymbol{J}_s^\perp|_{\text{interface}}$$

In metals, the spin torque is mostly "dampinglike"

$$\boldsymbol{T} = \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$$

magnetization

polarization



Stiles and Zangwill, Physical Review B 66, 014407 (2002)

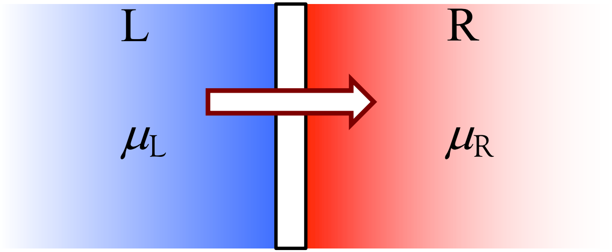
I. Spin Transfer Torque and Spin Pumping

a. Transfer of angular momentum

b. Spin pumping

Spin mixing conductance

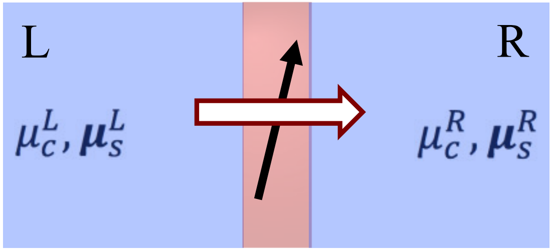
Basics of circuit theory



$$J_p = g(\mu_L - \mu_R)$$

$$g = \frac{2e^2}{Ah}\sum_{nm}|t'_{nm}|^2 = \frac{2e^2}{Ah}\sum_{nm}\delta_{nm} - |r_{nm}|^2$$

Interfacial conductance ($\Omega^{-1}.m^{-2}$)



Brataas, The European Journal of Physics B 22, 99 (2001)
Brataas, Physics Report 427, 157 (2006)

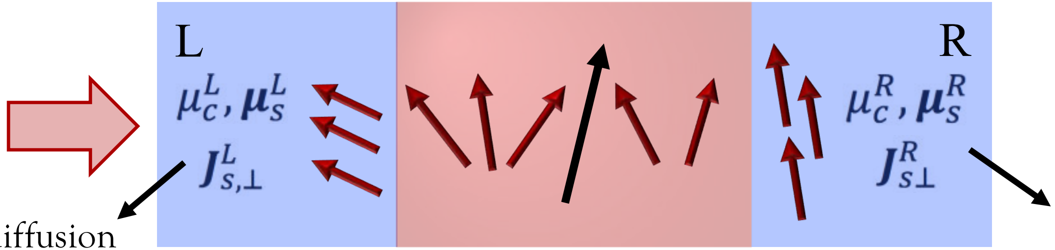
Generalization of Ohm's law

$$\boldsymbol{J}_{s,\perp}^L = 2\mathrm{Re}g_r^{\uparrow\downarrow}\boldsymbol{m}\times(\boldsymbol{\mu}_s^L\times\boldsymbol{m}) - 2\mathrm{Re}g_t^{\uparrow\downarrow}\boldsymbol{m}\times(\boldsymbol{\mu}_s^R\times\boldsymbol{m})$$
$$-2\mathrm{Im}g_r^{\uparrow\downarrow}\boldsymbol{m}\times\boldsymbol{\mu}_s^L + 2\mathrm{Im}g_t^{\uparrow\downarrow}\boldsymbol{m}\times\boldsymbol{\mu}_s^R$$

- This relation establishes a direction connection between the spin current and the spin accumulation
- All the spin physics (spin precession, relaxation, dephasing, scattering, magnetic texture etc.) is contained in just two coefficients

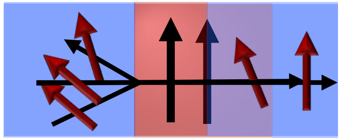
Spin mixing conductance

Spin flow

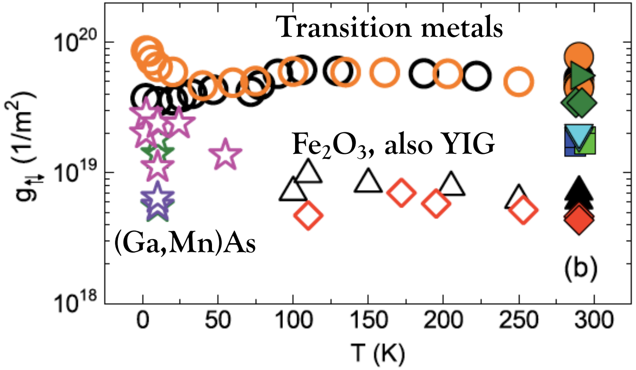


Drift-diffusion

Drift-diffusion

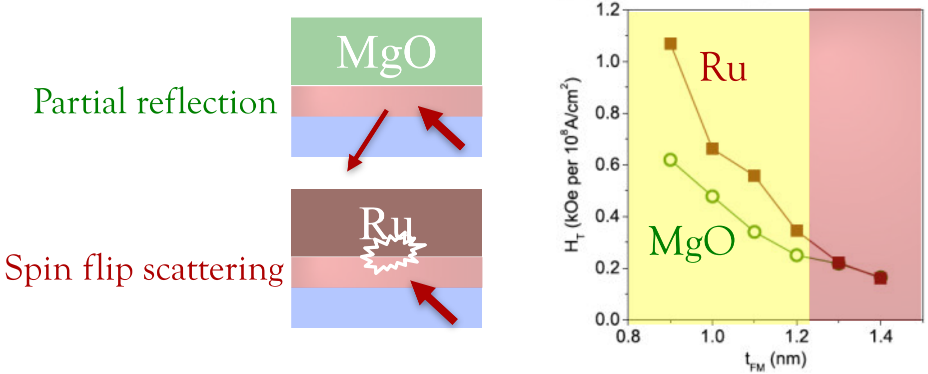


Reflected mixing conductance of various materials



Czeschka, Physical Review Letters 107, 046601 (2011)

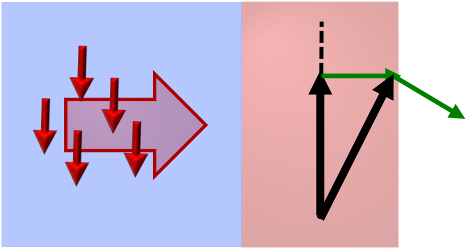
What if the spin current is not fully absorbed?



Qiu, Physical Review Letters 117, 217206 (2016)

Spin transfer torque and spin pumping

Spin transfer torque



Spin current

Torque on M

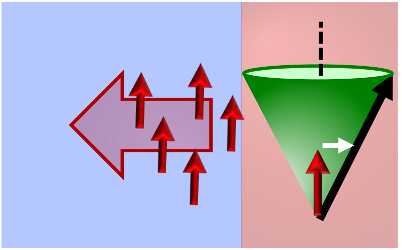
Magnetization dynamics

Spin current

Torque on s

Magnetization dynamics

Spin pumping



Onsager reciprocity

L. Onsager

Free energy

$$\mathcal{F}(\xi_i, \xi_j)$$

$$\partial_t \xi_i \qquad -\partial_{\xi_i}\mathcal{F}$$

Generalized current   Thermodynamics force

Anomalous Hall effect

$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

$$\sigma_{yx} = -\sigma_{xy}$$

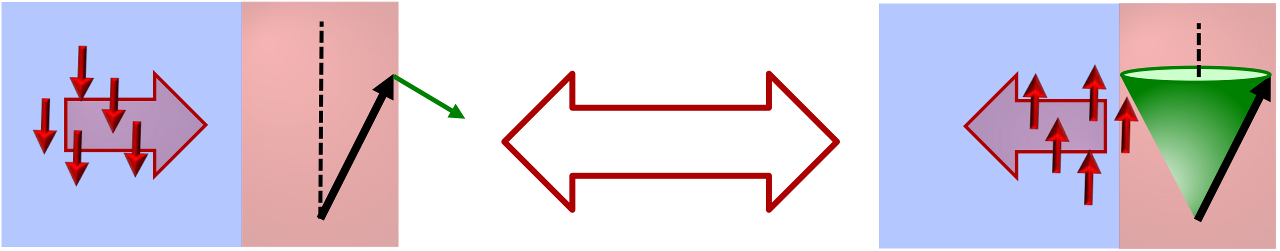
-1 if ξ_i is antisymmetric under time reversal

L. Onsager, Physical Review 37, 405 (1931)

Onsager reciprocity

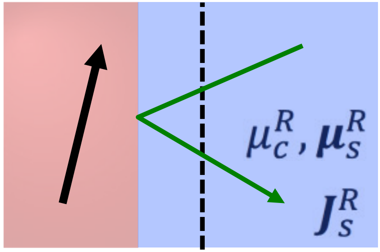
Spin transfer torque

Spin pumping



Current => Torque on M => Magnetization dynamics

Magnetization dynamics => Torque on s =>Spin pumping



Spin current definition $e\boldsymbol{J}_s = -2\mathrm{Re}g_r^{\uparrow\downarrow}\boldsymbol{m}\times(\boldsymbol{\mu}_s\times\boldsymbol{m}) + 2\mathrm{Im}g_r^{\uparrow\downarrow}\boldsymbol{m}\times\boldsymbol{\mu}_s$

Landau-Lifshitz equation $\partial_t\boldsymbol{M} = |\gamma|\boldsymbol{M}\times\partial_{\boldsymbol{M}}W - (\mu_B/d)\boldsymbol{J}_s$

Generalized currents (1/s)

$$\begin{pmatrix} A\boldsymbol{J}_s \\ \partial_t\boldsymbol{m} \end{pmatrix}$$

Generalized forces (eV)

$$\begin{pmatrix} e\boldsymbol{\mu}_s \\ -\partial_{\boldsymbol{M}}W \end{pmatrix}$$

Spin injection — Spin pumping

$$\begin{pmatrix} A\boldsymbol{J}_s \\ \partial_t\boldsymbol{m} \end{pmatrix} = \begin{pmatrix} \hat{\mathcal{L}}_{ss} & \hat{\mathcal{L}}_{sm} \\ \hat{\mathcal{L}}_{ms} & \hat{\mathcal{L}}_{mm} \end{pmatrix} \begin{pmatrix} e\boldsymbol{\mu}_s \\ \boldsymbol{F} \end{pmatrix}$$

Spin transfer torque — Magnetic precession

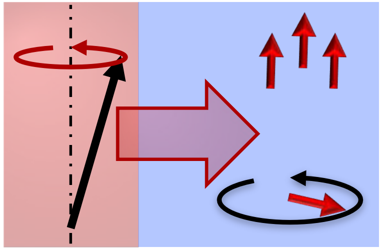
$$\mathcal{L}_{sm}^{ij}(\boldsymbol{m}) = \mathcal{L}_{ms}^{ji}(-\boldsymbol{m})$$

$$\boldsymbol{J}_s = \frac{1}{4\pi}\frac{h}{e^2}\left[2\mathrm{Re}g_r^{\uparrow\downarrow}\boldsymbol{m}\times\partial_t\boldsymbol{m} + 2\mathrm{Im}g_r^{\uparrow\downarrow}\partial_t\boldsymbol{m}\right]$$

Brataas et al., in *Spin Current*, eds. Maekawa, Valenzuela, Saitoh, and Kimura (OUP, 2012)

The spin battery (Tutoooorial!)

The spin battery concept



FMR as a source of pure spin current

Brataas Physical Review B 66, 060404(R) (2002)

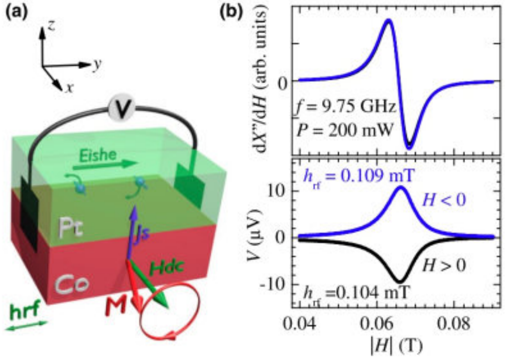
Consider a precessing magnetization

$$\boldsymbol{m} = \cos\theta\, \boldsymbol{z} + \sin\theta\, (\cos\omega t\, \boldsymbol{x} + \sin\omega t\, \boldsymbol{y})$$

$$\frac{\hbar}{2}\boldsymbol{J}_s^{dc} = \frac{\hbar\omega}{4\pi}\mathrm{Re}\tilde{g}_r^{\uparrow\downarrow}\sin^2\theta\, \boldsymbol{z}$$

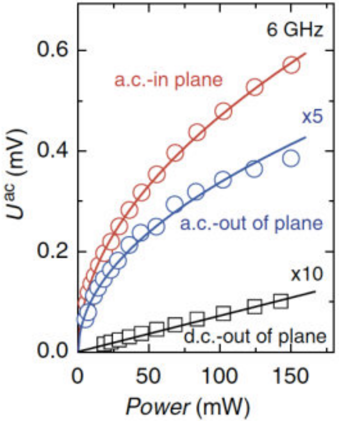
$$\frac{\hbar}{2}\boldsymbol{J}_s^{ac} = -\frac{\hbar\omega}{16\pi}\mathrm{Re}\tilde{g}_r^{\uparrow\downarrow}\sin 2\theta\, (\cos\omega t\, \boldsymbol{x} + \sin\omega t\, \boldsymbol{y})$$

Jiao, Bauer Physical Review Letters 110, 217602 (2013)

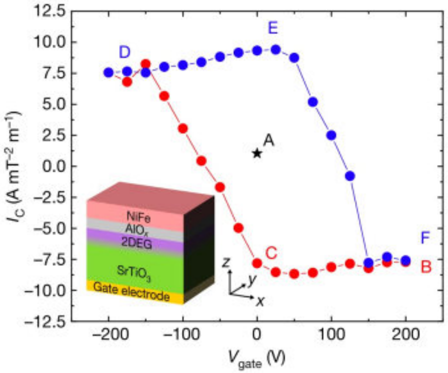


Saitoh et al., Appled Physical Letters 88, 182509 (2006)

Rojas-Sanchez et al. Physical Review Letters 112, 106602 (2014)



Wei et al., Nature Communications 5, 3768 (2014)



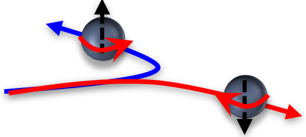
Noel et al., Nature 580, 483 (2020)

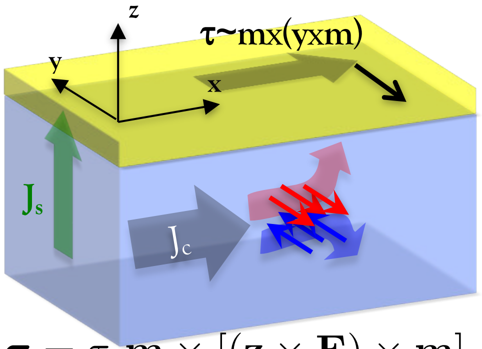
Quick escape in spin-orbitland

Spin-orbit physics at interfaces

Spin Hall effect

$$\hat{\mathbf{v}}_s = \partial_{\hbar\mathbf{k}}\varepsilon^s_{\mathbf{k}} + s\hat{\mathbf{\Omega}}_{\mathbf{k}} \times \dot{\mathbf{k}}$$

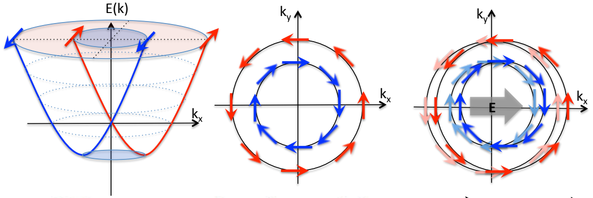




$$\boldsymbol{\tau} = \tau_{\|}\mathbf{m} \times [(\mathbf{z} \times \mathbf{E}) \times \mathbf{m}]$$

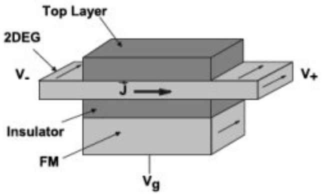
See Haney et al., PRB 87, 174411 (2013)

Inverse spin galvanic (Rashba) effect



$$H_{\mathrm{R}} \approx -\alpha\hat{\boldsymbol{\sigma}} \cdot (\mathbf{z} \times \mathbf{k}) \qquad \vec{S} \propto \vec{z} \times \vec{j}_e$$

Ivchenko, Pikus, P. Zh. Eksp. Teor. Fiz 27, 604 (1978)
Edelstein, Solid State Com. 73, 233 (1990)

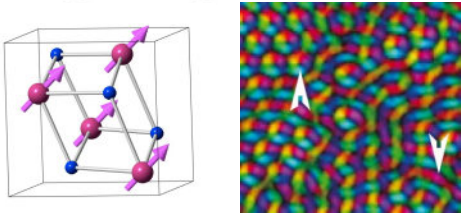


$$\boldsymbol{\tau} = \tau_{\perp}\mathbf{m} \times (\mathbf{z} \times \mathbf{E})$$

Manchon & Zhang, PRB 78, 212405 (2008)

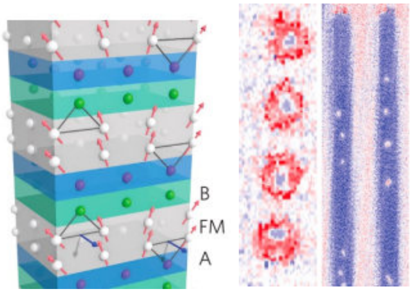
Dzyaloshinskii-Moriya Interaction

$$W_{3\mathrm{D}} = D_{3\mathrm{D}}\mathbf{m} \cdot (\boldsymbol{\nabla} \times \mathbf{m}).$$

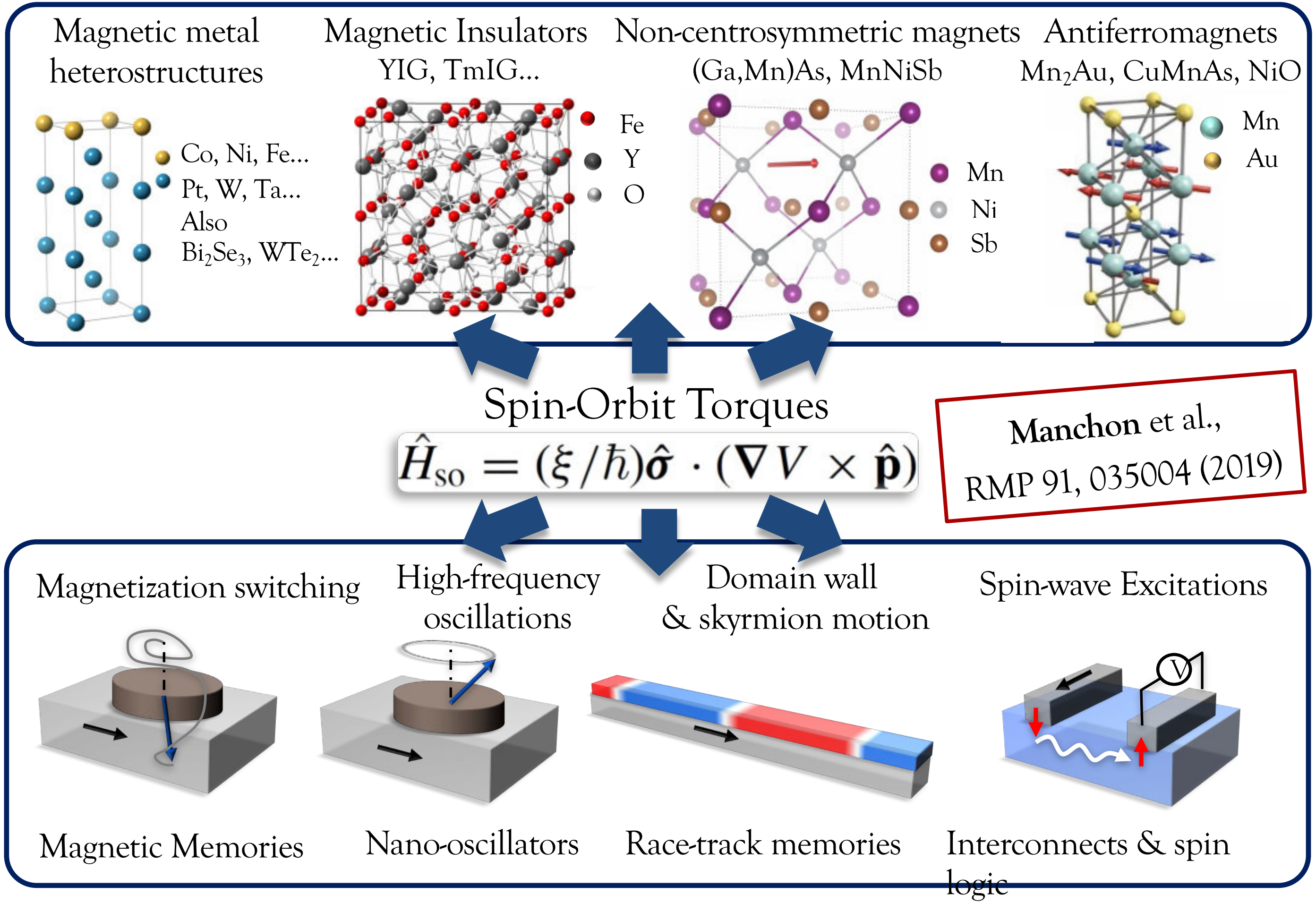


Yu, Nature 465, 901 (2010)

$$W_{2\mathrm{D}} = D_{2\mathrm{D}}\mathbf{m} \cdot [(\mathbf{z} \times \boldsymbol{\nabla}) \times \mathbf{m}].$$



Moreau-Luchaire, Nat. Nano 11, 444 (2016)


Magnetic metal heterostructures
Co, Ni, Fe...
Pt, W, Ta...
Also
Bi_2Se_3, WTe_2...
Magnetic Insulators
YIG, TmIG...
Fe
Y
O
Non-centrosymmetric magnets
(Ga,Mn)As, MnNiSb
Mn
Ni
Sb
Antiferromagnets
Mn_2Au, CuMnAs, NiO
Mn
Au
Spin-Orbit Torques
$\hat{H}_{so} = (\xi/\hbar)\hat{\boldsymbol{\sigma}} \cdot (\boldsymbol{\nabla} V \times \hat{\mathbf{p}})$
Manchon et al.,
RMP 91, 035004 (2019)
Magnetization switching
High-frequency oscillations
Domain wall & skyrmion motion
Spin-wave Excitations
V
Magnetic Memories
Nano-oscillators
Race-track memories
Interconnects & spin logic

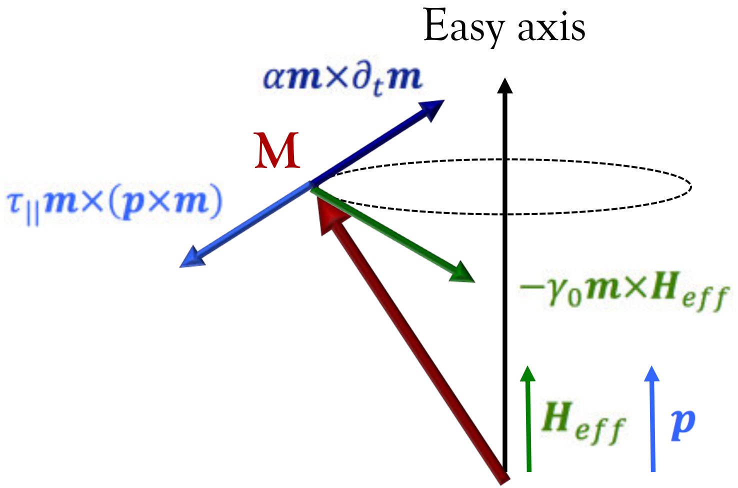
II. Current-driven magnetization dynamics

a. Switching

b. Self-sustained oscillations

Current-driven switching and excitations

$$\partial_t \boldsymbol{m} = -\gamma_0 \boldsymbol{m}\times\boldsymbol{H}_{eff} + \alpha \boldsymbol{m}\times\partial_t \boldsymbol{m} + \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$$

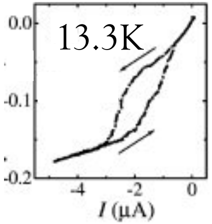


$\alpha \boldsymbol{m}\times\partial_t \boldsymbol{m} > \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ **M** relaxes towards H_{eff}

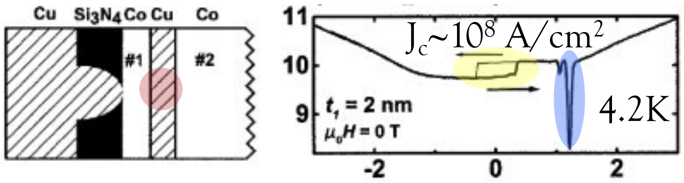
$\alpha \boldsymbol{m}\times\partial_t \boldsymbol{m} < \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ **M** switches towards -H_{eff}

$\alpha \boldsymbol{m}\times\partial_t \boldsymbol{m} = \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ **M** precesses about H_{eff}

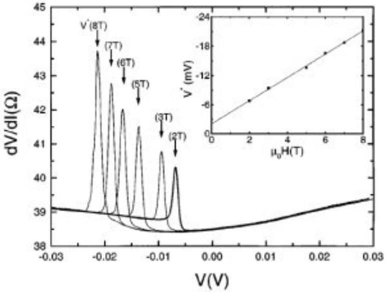
$La_{0.67}Sr_{0.33}MnO/SrTiO_3$
A~170x170 A^2, J_c~10^5 A/cm^2
Thermally activated switching



Sun, Journal of Magnetism and Magnetic Materials 202, 157 (1999)



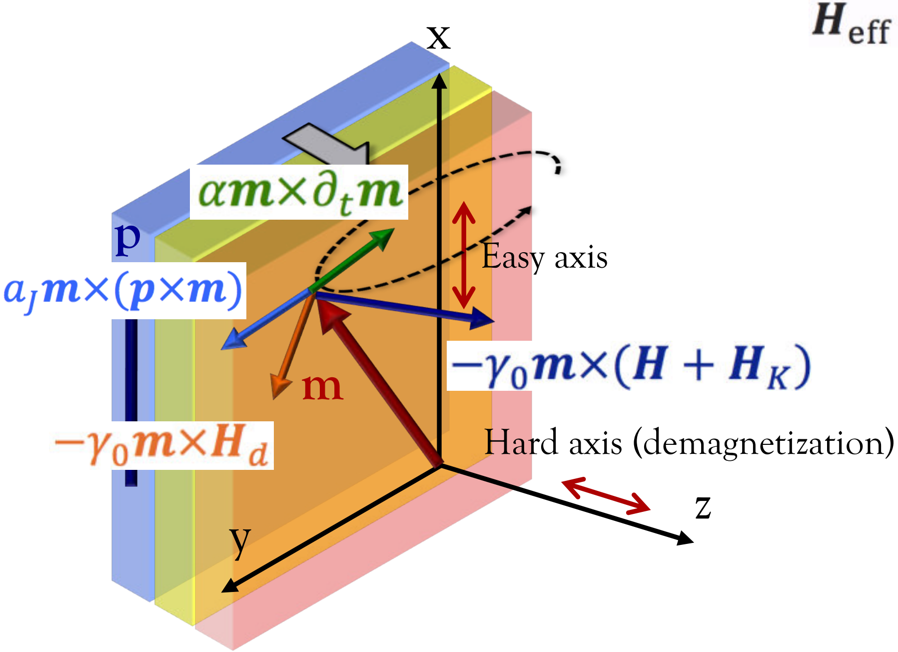
Myers, Science 285, 867 (1999)



Magnetic excitations
J_c~10^9 A/cm^2 @ 4.2K

Tsoi, Physical Review Letters 80, 4281 (1998)

Stability diagram and critical switching current



$$\partial_t \boldsymbol{m} = -\gamma_0 \boldsymbol{m}\times\boldsymbol{H}_{\text{eff}} + \alpha \boldsymbol{m}\times\partial_t \boldsymbol{m} + a_J \boldsymbol{m}\times(\boldsymbol{x}\times\boldsymbol{m})$$

$$\boldsymbol{H}_{\text{eff}} = H\boldsymbol{x} + H_K m_x \boldsymbol{x} - H_d m_z \boldsymbol{z}$$

Field + uniaxial anisotropy — Demagnetizing field

$$m_{y,z} \propto e^{-i\omega t} \equiv e^{\text{Im}[\omega]t} e^{-i\text{Re}[\omega]t}$$

Stability conditions

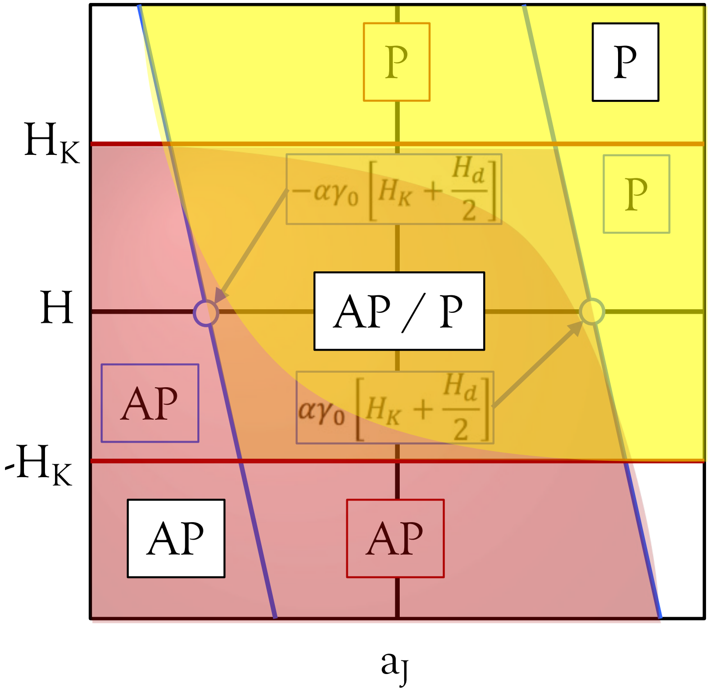
$$m_x = 1, \text{Im}\omega > 0 \Rightarrow a_J < -\alpha\gamma_0 \left[H + H_K + \frac{H_d}{2}\right]$$

$$m_x = -1, \text{Im}\omega > 0 \Rightarrow a_J > \alpha\gamma_0 \left[-H + H_K + \frac{H_d}{2}\right]$$

Stability diagram and critical switching current

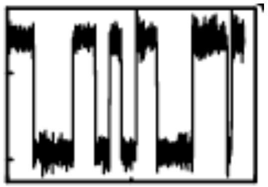
$$P \rightarrow AP \Rightarrow a_J < -\alpha\gamma_0 \left[H + H_K + \frac{H_d}{2}\right]$$

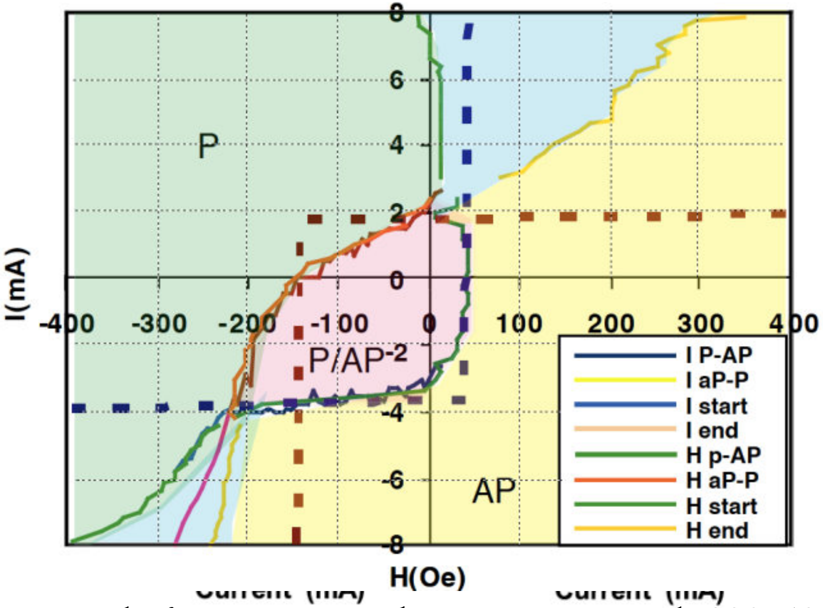
$$AP \rightarrow P \Rightarrow a_J > \alpha\gamma_0 \left[-H + H_K + \frac{H_d}{2}\right]$$



Thermal activation

Resistance fluctuation
due to superparamagnetism



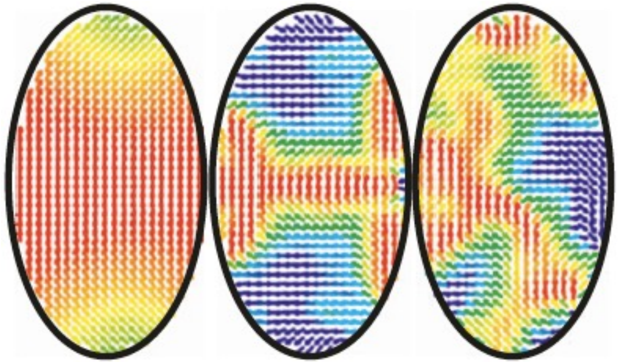


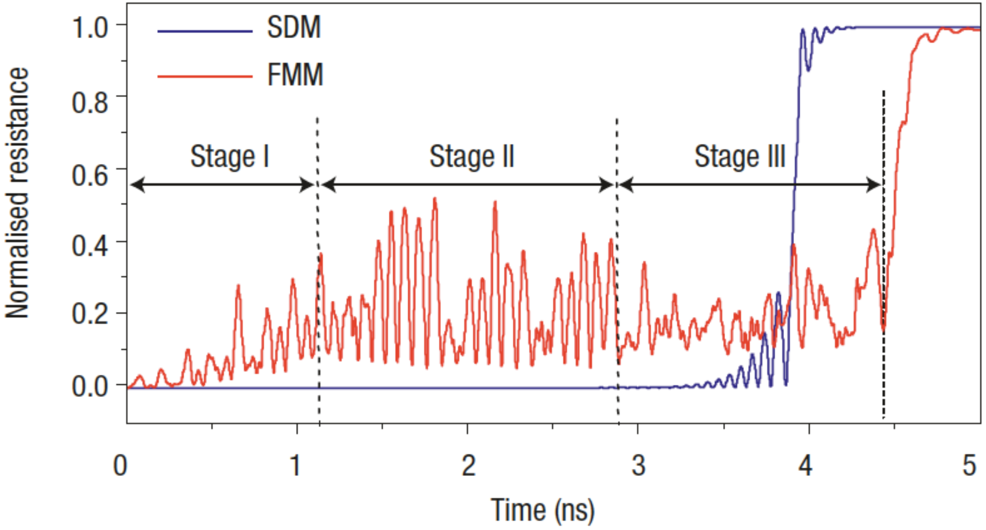
Deac, Journal of Magnetism and Magnetic Materials 290, 42 (2005)

Krivorotov, Physical Review Letters 93, 166603 (2004)

Stability diagram and critical switching current

Simulation of macrospin switching





Lee et al., Nature Materials 3, 877 (2004)

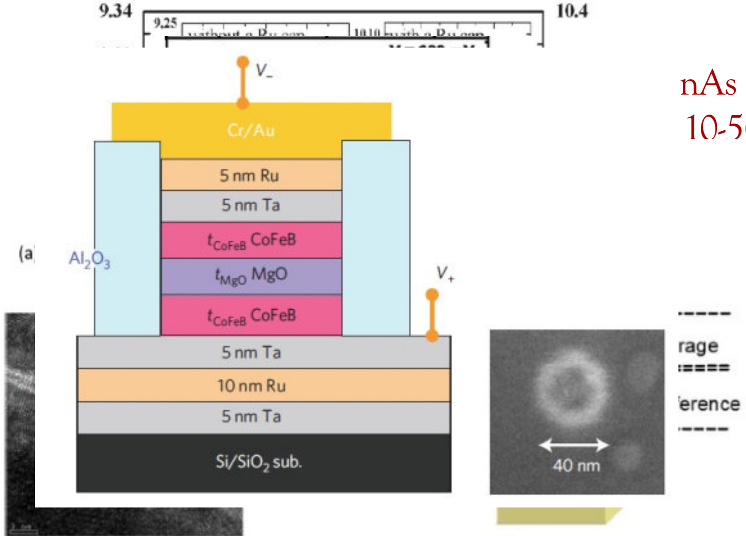
Strategies to optimize the critical switching current

Torque efficiency

$$a_J = \frac{P\mu_B}{eM_s d} j_c$$

Current threshold

$$j_{th} = \pm \frac{\alpha M_s d}{P} \left(\frac{2e}{\hbar}\right) \mu_0 \left(H_K + \frac{H_d}{2} \mp H\right)$$



nAs
10-50 emu/cm^3
0K

mu/cm^3
00-900 K

Cu
Cu

Ikdea, Nature Materials 9, 721 (2010)

Apalko, Proceeding of the IEEE 104, 1796 (2016)

Typical current densities: $10^5 - 10^7$ A/cm^2

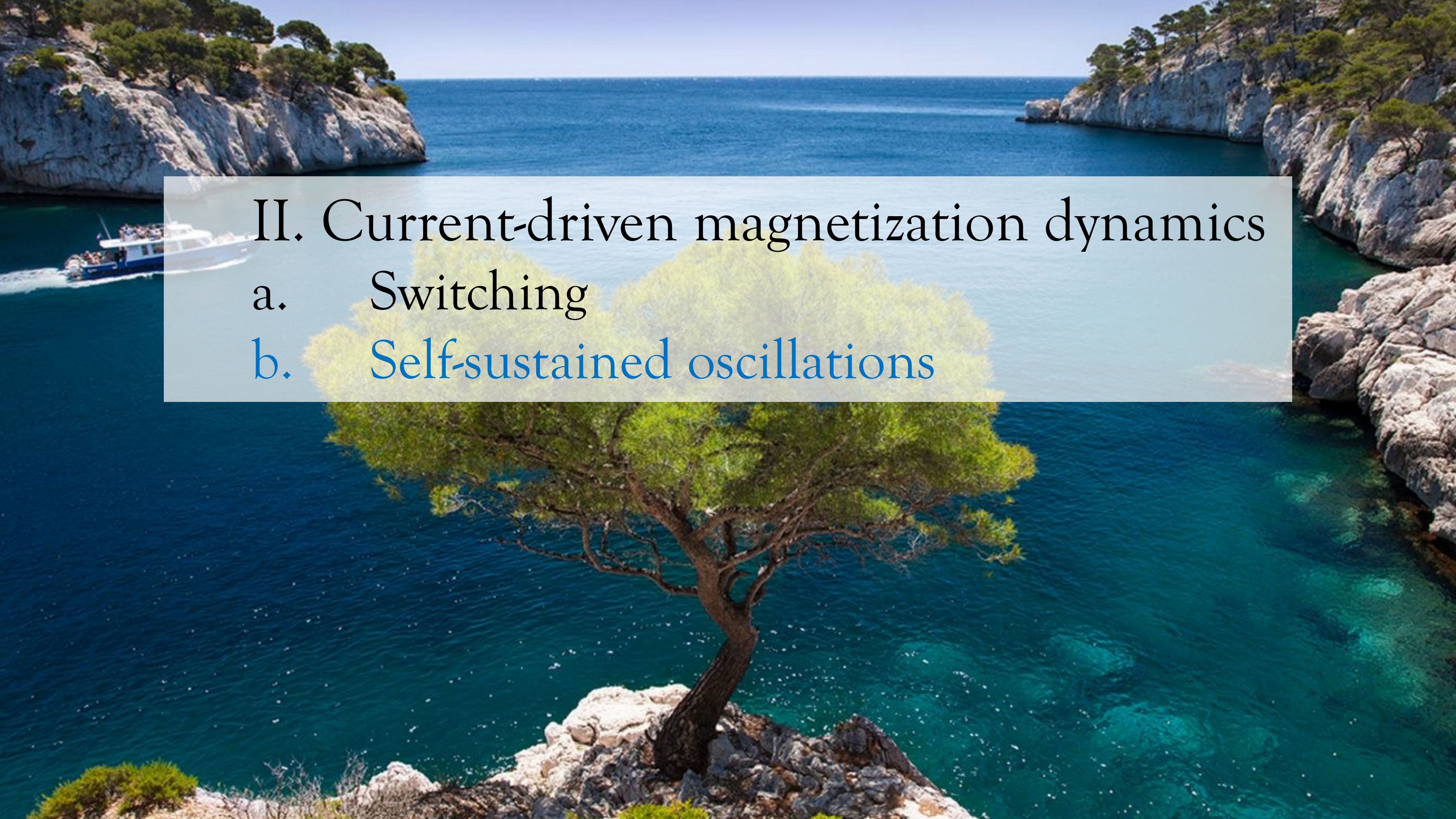
Ikeda, Nature Materials 5, 210 (2006)

Ouna...

Requires tiny pillars ~ 100 x 100 nm^2

Yagami, Applied Physics Letters 85, 5634 (2004)

Qiu, Physical Review Letters 117, 217206 (2016)



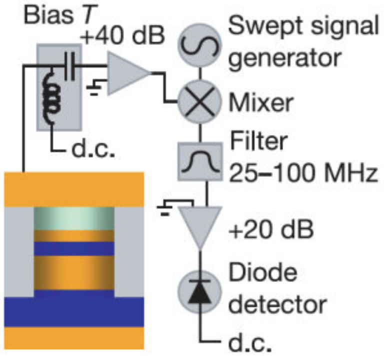
II. Current-driven magnetization dynamics

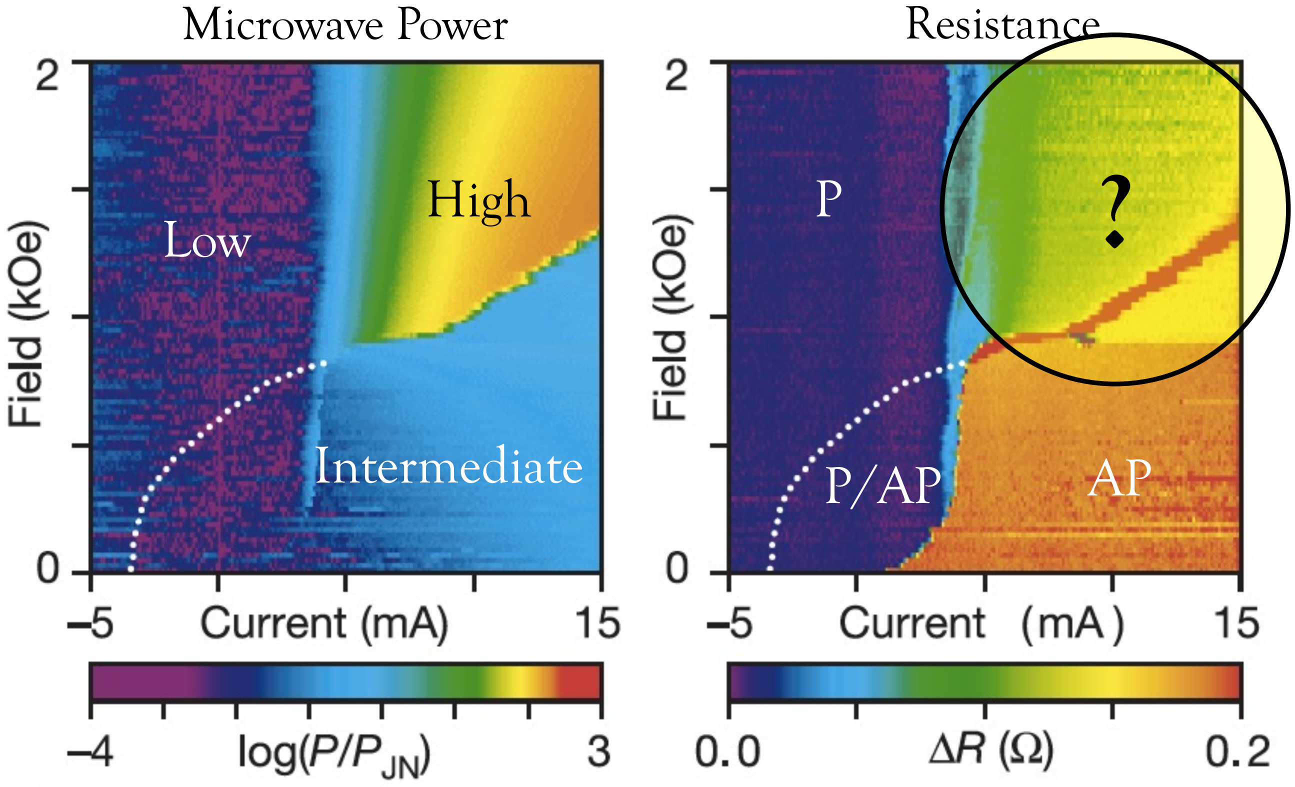
a. Switching

b. Self-sustained oscillations

Beyond current-driven switching

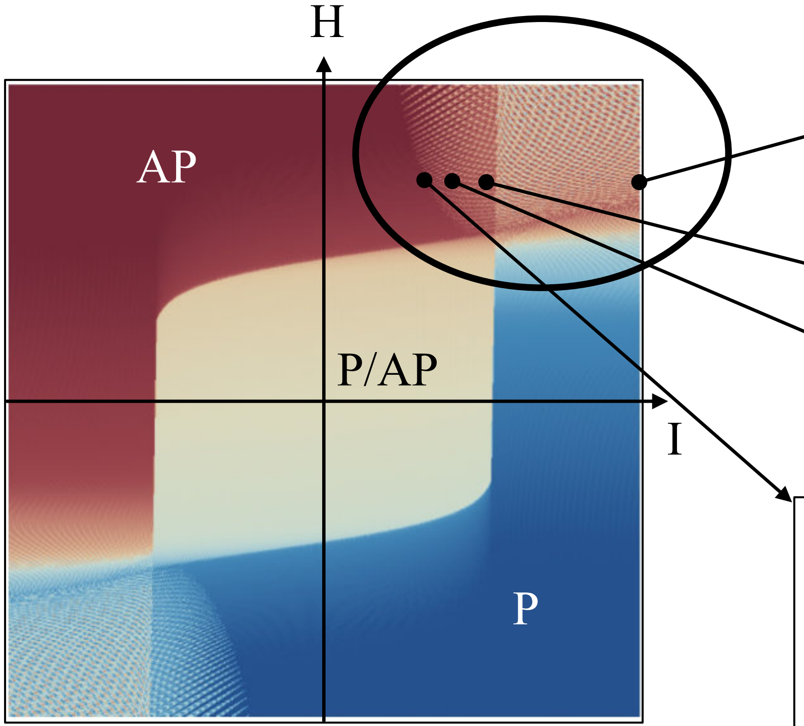
Co(40)/Cu(3)/Co(10)

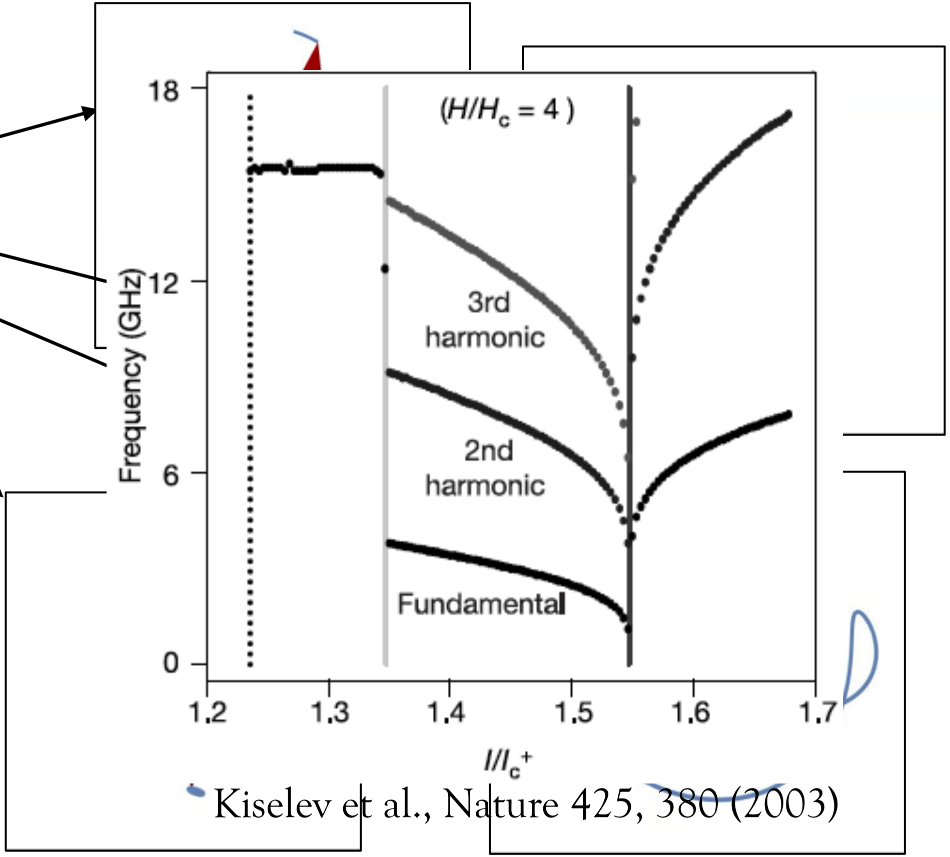




Kiselev, Nature 425, 380 (2003)

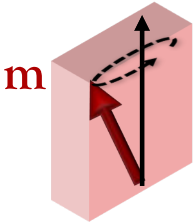
Current-driven self-oscillations





Kiselev et al., Nature 425, 380 (2003)

Current-driven self-oscillations



Phenomenological theory

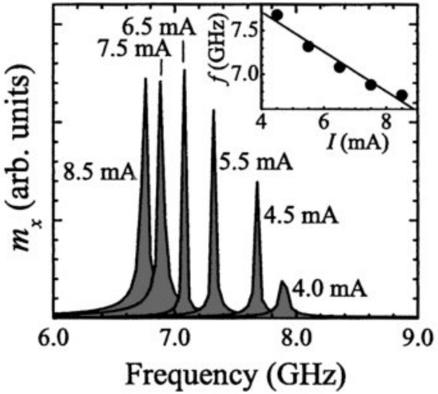
$$c(t) = r(t)e^{i\phi(t)}$$

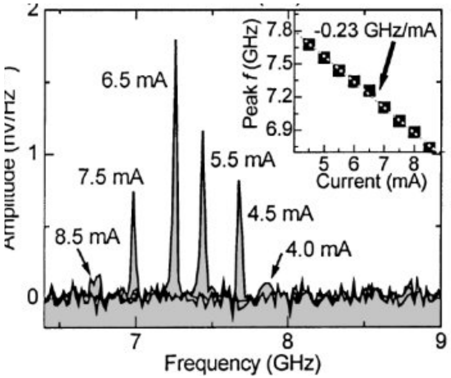
$$\begin{cases} \partial_t r = -(\Gamma - \sigma I + \sigma I r^2) r \\ \partial_t \phi = -(\omega + N r^2) \end{cases}$$

$$\zeta = \frac{\sigma I}{\Gamma}$$

$$\boxed{\partial_t r = -\Gamma(1 - \zeta + \zeta r^2) r}$$

$$\zeta \leq 1 \Rightarrow r_0 = 0 \qquad \zeta > 1 \Rightarrow r_0^2 = \frac{\zeta - 1}{\zeta}$$

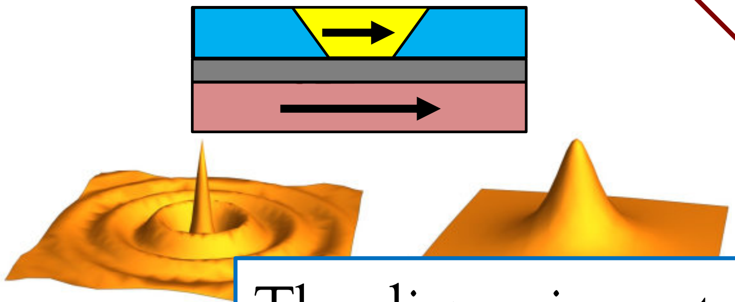


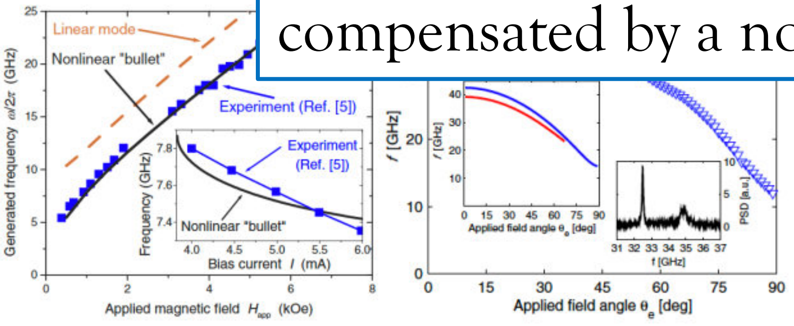


J.V. Kim, *Spin-Torque Oscillators*, in Solid State Physics 63, 2012
Rippard et al., Physical Review Letters 92, 027201 (2004)

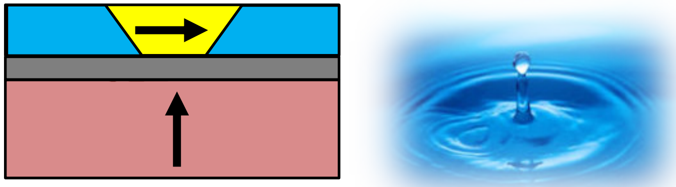
Current-driven self-oscillations

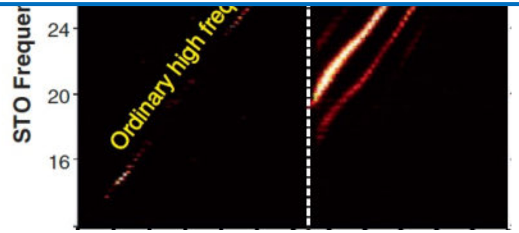
Bullets and droplets

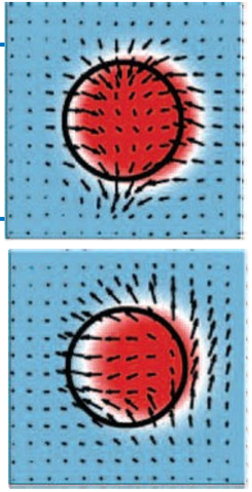




Slavin and Tiberkevich, Physical Review Letters 95, 237201 (2005)
Bonetti et al., Physical Review Letters 105, 217204 (2010)





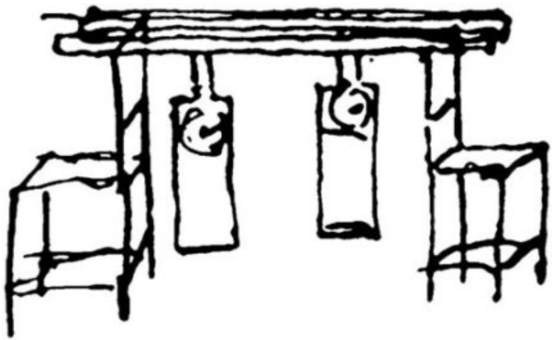


The dispersive nature of a wave (exchange) is compensated by a nonlinearity (anisotropy)

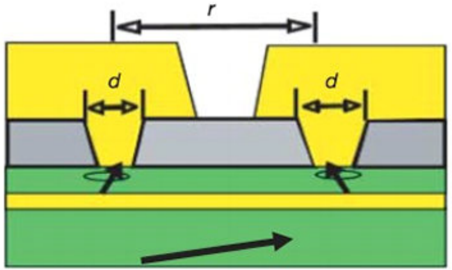
Hoefer et al., Physical Review B 82, 054432 (2010)
Mohseni et al., Science 339, 1295 (2013)

Current-driven self-oscillations

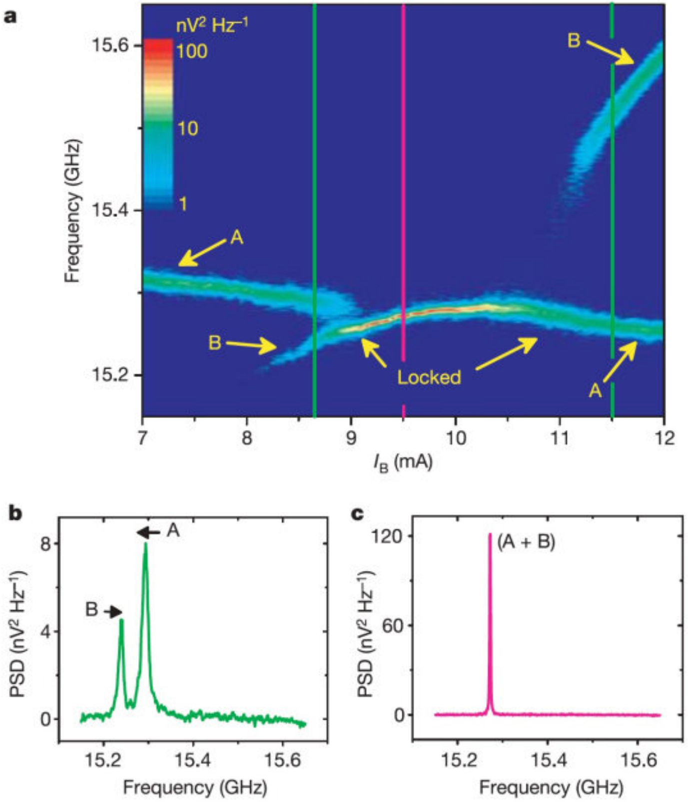
Synchronization between nano-oscillators



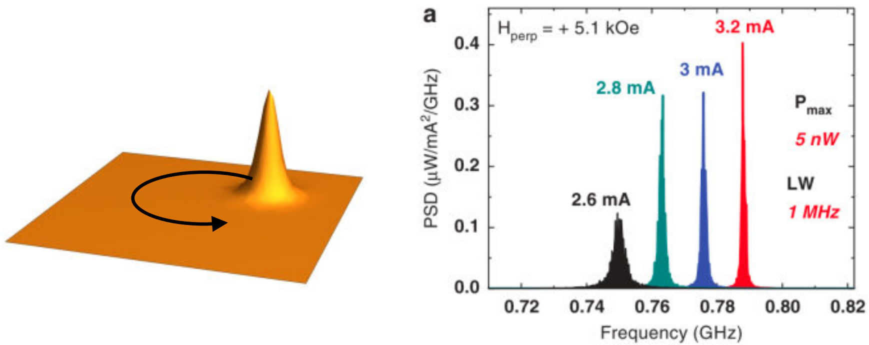
Hyungens, *Horologium Oscillatorium*, 1673



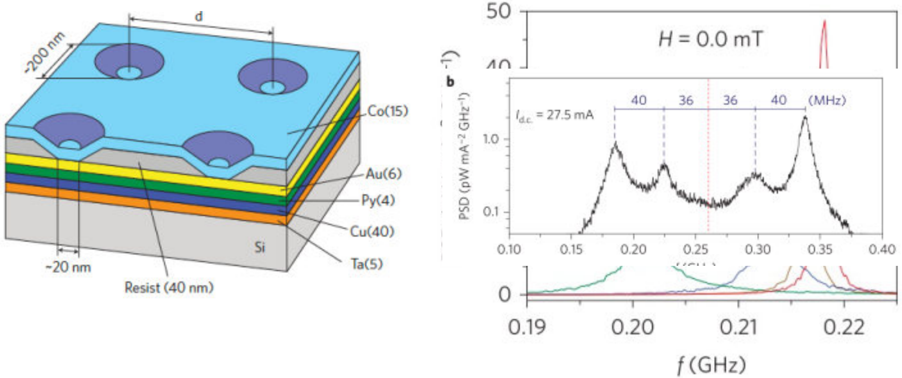
Mancoff, Nature Nanotechnology 437, 393 (2005)
Kaka, Nature Nanotechnology 437, 389 (2005)



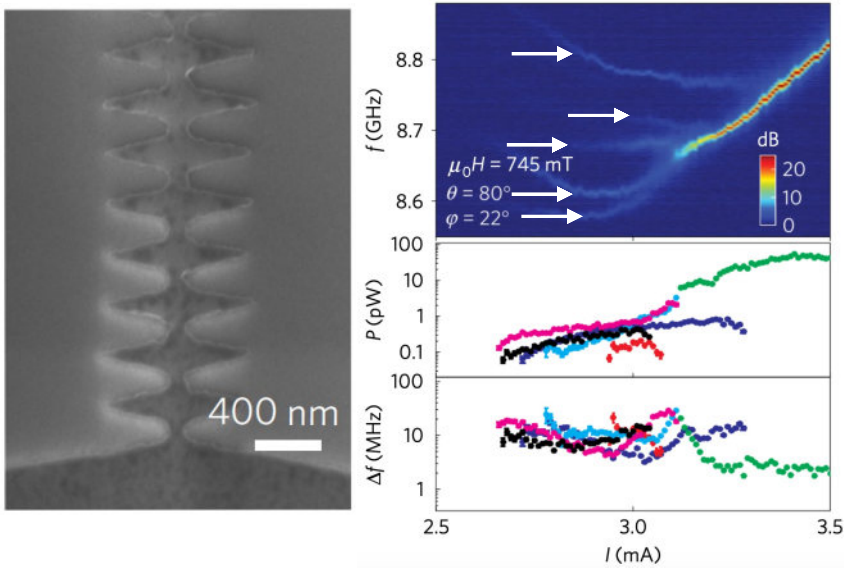
Current-driven self-oscillations



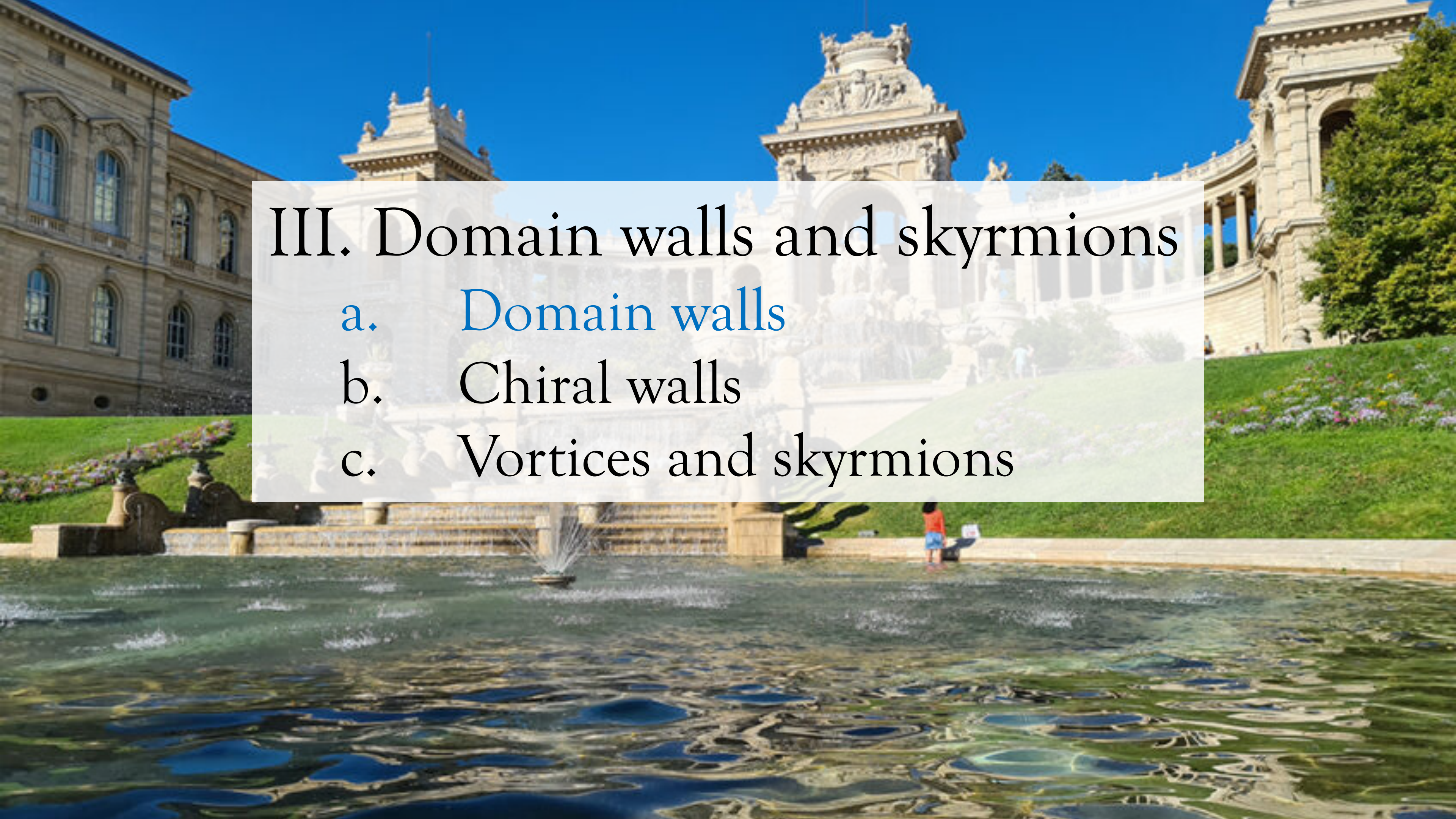
Dussaux, Nature Communications 10, 1038 (2010)



Ruotolo, Nature Nanotechnology 4, 528 (2009)



Awad et al., Nature Physics 13, 292 (2016)



III. Domain walls and skyrmions

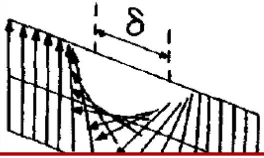
a. Domain walls

b. Chiral walls

c. Vortices and skyrmions

Current-driven magnetic domain wall motion

Spin torque in magnetic domain walls



L. Ber

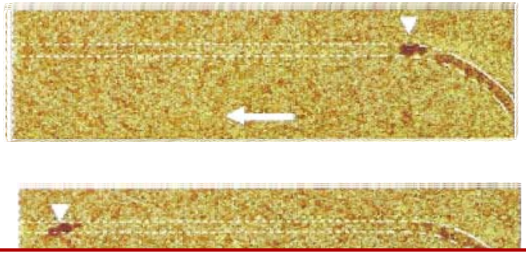
“As ar
follow
magnetization $\mathbf{M}_s$.”

In other words, “$\mathbf{M}_s$ applies an exchange torque on **s**. Inversely, s creates a reaction torque on the wall.”

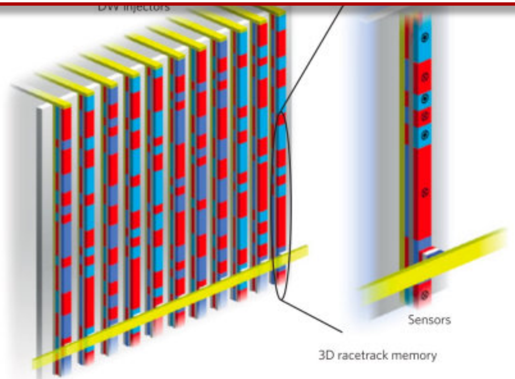
$$H_{ex} = \frac{1}{\delta}\frac{P\hbar}{eM_s}J_c$$

Berger, Journal of Applied Physics 49, 2156 (1978)
Berger, Journal of Applied Physics 55, 1954 (1984)

Thomas & Parkin, in *Handbook of Magnetism and Advanced Magnetic Materials*
Beach, Journal of Magnetism and Magnetic Materials 320, 1272 (2008)
Boulle, Materials Science and Engineering: R: Reports 72, 159 (2011)
Grollier, Comptes Rendus de Physique 12, 309 (2011)



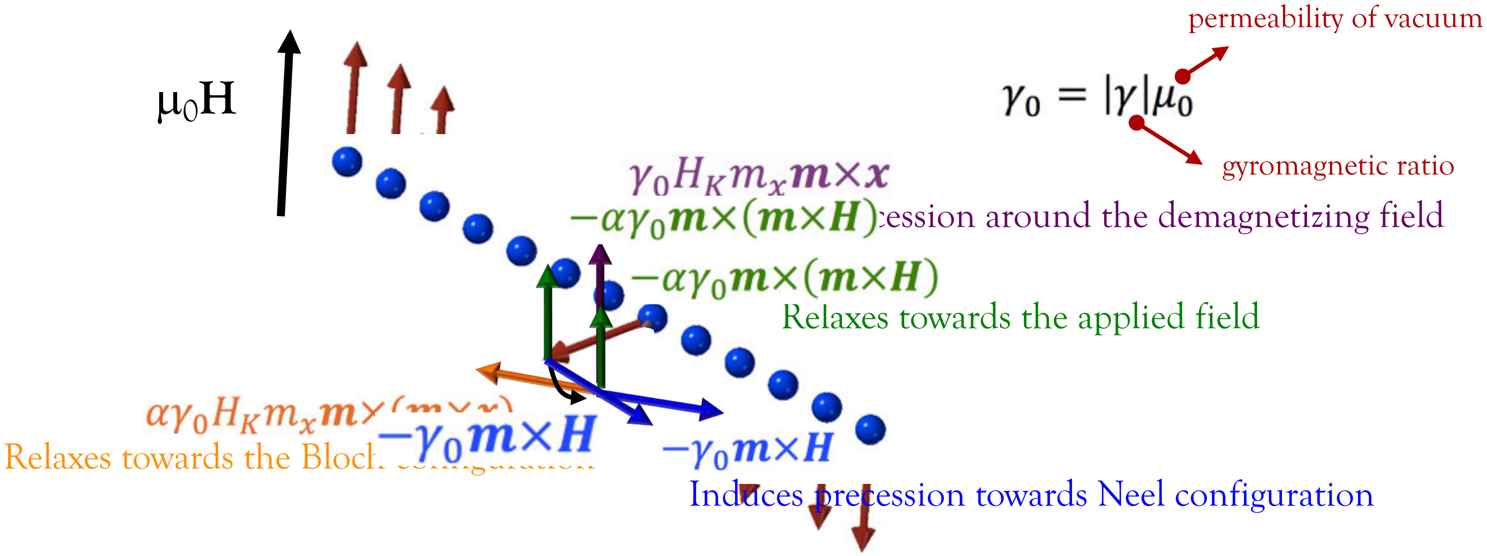
ier EPL 2004…



Parkin, Science 320, 190 (2008); Nature Nanotechnology 10, 195 (2015)

The basic of field-driven motion

A reminder about field-driven domain wall motion



As long as the field torque compensates the demagnetizing damping: steady motion
As soon as the field torque exceeds the demagnetizing damping: precessional motion

One-dimensional model

Domain wall profile

Dipolar energy (favor Bloch over Néel)

$$W = A(\partial_x \boldsymbol{m})^2 - K_\perp m_z^2 + K_d m_x^2$$

Exchange   Perpendicular anisotropy

$$\boldsymbol{m} = (\cos\varphi \sin\theta \,, \sin\varphi \sin\theta \,, \cos\theta)$$

chirality   velocity   width

$$\theta(x,t) = 2 \arctan e^{s(x-vt)/\Delta}$$

$$\varphi = \varphi(t), \Delta =$$

Current-driven Motion is only allowed above Walker breakdown (precessional motion regime)

How does the torque look like?

$$\boldsymbol{T} = \tau_{||} \boldsymbol{m} \times ($$

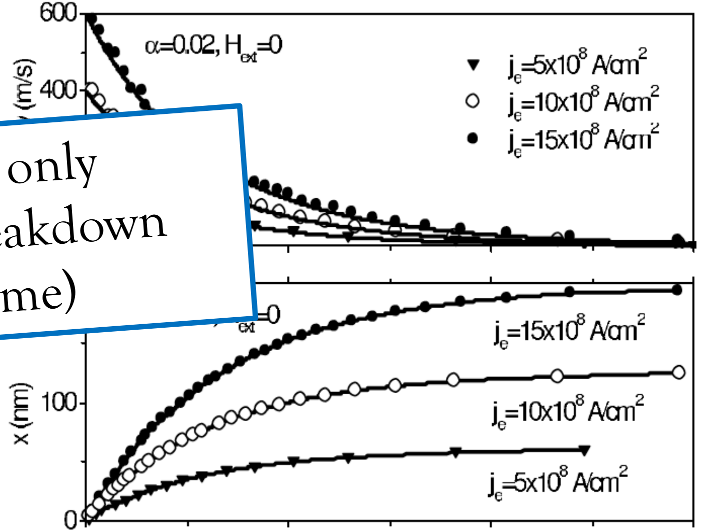
What does it do?

Berger's field

$$b_J = \frac{P\mu_B}{eM_s} J_c \quad \Delta\partial_t\varphi = s\frac{\gamma_0 \Delta H_K}{2} \sin$$

$$\Delta\partial_t\varphi = 0$$

$$H_{ex} = \frac{1}{\delta}\frac{P\hbar}{eM_s} J_c \boldsymbol{m}$$



Li and Zhang, Physical Review Letters 92, 207203 (2004)

One-dimensional model

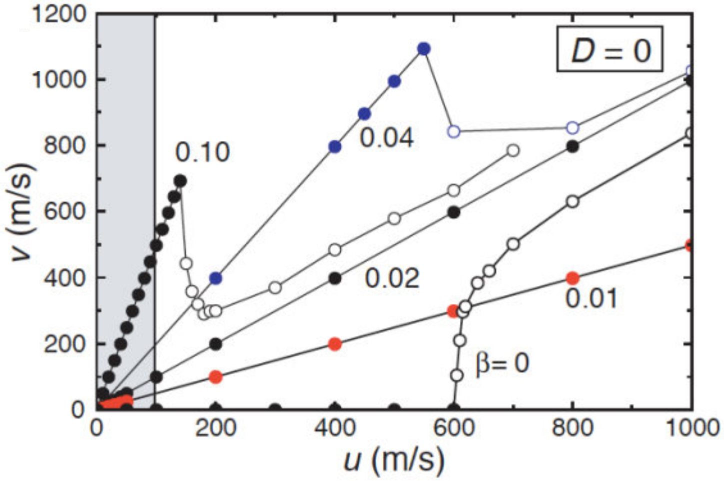
How to break the compensation between the adiabatic torque and the dipolar energy?

$$\partial_t \boldsymbol{m} = -\gamma_0 \boldsymbol{m}\times\boldsymbol{H}_{\text{eff}} + \alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} - b_J\partial_x\boldsymbol{m} + \beta b_J\boldsymbol{m}\times\partial_x\boldsymbol{m}$$

Non-adiabatic torque

$$\partial_t\varphi = \alpha\frac{\gamma_0 H_K}{2}\sin 2\varphi + (\beta-\alpha)b_J\frac{s}{\Delta}$$

$$v\frac{s}{\Delta} = -\frac{\gamma_0 H_K}{2}\sin 2\varphi + \frac{s}{\Delta}(1+\alpha\beta)b_J$$



Thiaville, Europhysics Letters 69, 990 (2005)
Zhang, Physical Review Letters 93, 127204 (2004)

Below Walker breakdown

$$\partial_t\varphi = 0$$

$$\frac{\gamma_0 H_K}{2}\sin 2\varphi = \frac{s}{\Delta}\left(1-\frac{\beta}{\alpha}\right)b_J$$

$$v = \frac{\beta}{\alpha}b_J$$

Driven by the non-adiabatic torque

Above Walker breakdown

$$\partial_t\varphi \neq 0$$

$$v = b_J$$

Driven by the adiabatic torque

The origin of the non-adiabatic torque

$$\partial_t \boldsymbol{s} = -\nabla\cdot \boldsymbol{J}_s - \frac{1}{\tau_\Delta}\boldsymbol{s}\times\boldsymbol{m} - \frac{1}{\tau_\varphi}\boldsymbol{m}\times(\boldsymbol{s}\times\boldsymbol{m}) - \frac{1}{\tau_{sf}}\boldsymbol{s}$$

Spin current Spin precession Spin dephasing Spin relaxation

Zhang, Physical Review Letters 93, 127204 (2004)

$$b_J = \frac{P\mu_B}{eM_s}J_c$$

Spin drift velocity

$$\boldsymbol{T} = \boldsymbol{T} = (1-\beta\xi)b_J\partial_x\boldsymbol{m} - b_J\beta\boldsymbol{m}\times\partial_x\boldsymbol{m}' \cdot \boldsymbol{J}_s]$$

$$\boldsymbol{J}_s = -P\frac{J_c}{e}\boldsymbol{m} \Rightarrow \int d\Omega \boldsymbol{J}_s = -\frac{P\mu_B}{eM_s}J_c\boldsymbol{m}$$

$$\xi = \frac{\tau_\Delta}{\tau_\varphi} + \frac{\tau_\Delta}{\tau_{sf}}$$

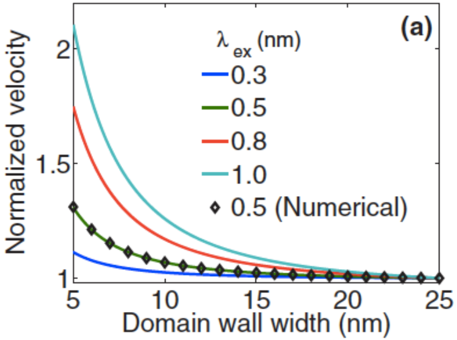
$$\beta = \frac{\tau_\Delta}{\tau_{sf}}\frac{1}{1+\xi^2}$$

Non-adiabaticity parameter

$$\boldsymbol{J}_s = -b_J\boldsymbol{m} - D\partial_x\boldsymbol{s}$$

Spin diffusion

$$\boldsymbol{T} = (1-\xi\beta)b_J\partial_x\boldsymbol{m} - \beta b_J\boldsymbol{m}\times\partial_x\boldsymbol{m} + \lambda_\Delta^2 b_J\partial_x^2[\boldsymbol{m}\times\partial_x\boldsymbol{m}]$$



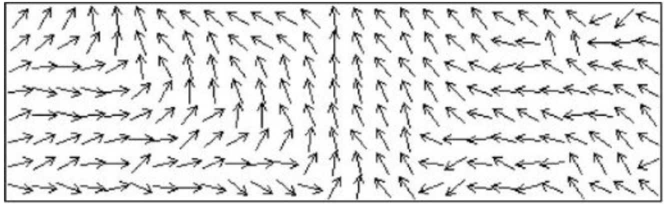
Akosa et al., Physical Review B 91 094411 (2015)

Experimental observations

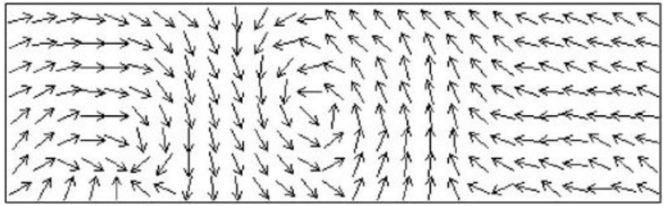
Current-driven domain wall motion in permalloy

$$M_s = 800\ emu/cm^3, \alpha = 0.005$$
$$\Delta = 50\ nm, P = 0.4$$

Transverse wall

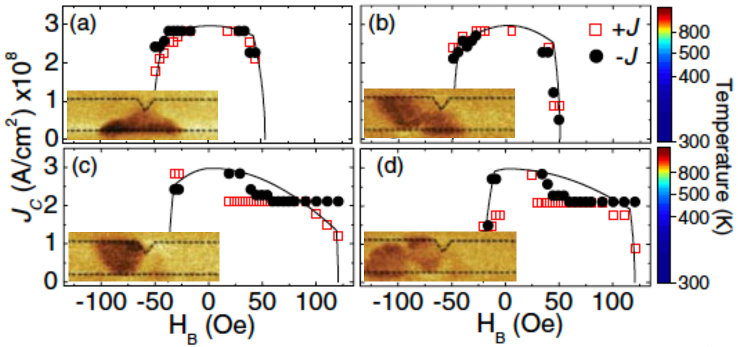


Vortex wall



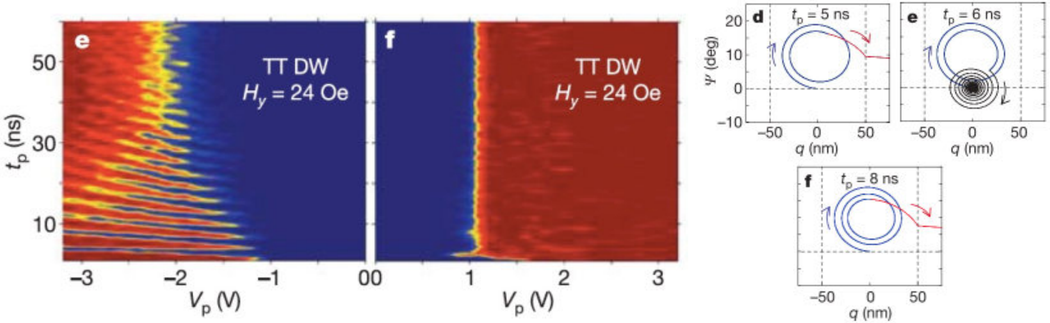
Klaui, Physical Review Letters 95, 026601 (2005)

Quasi-static current



Hayashi, Physical Review Letters 97, 207205 (2006)

Nanosecond pulse

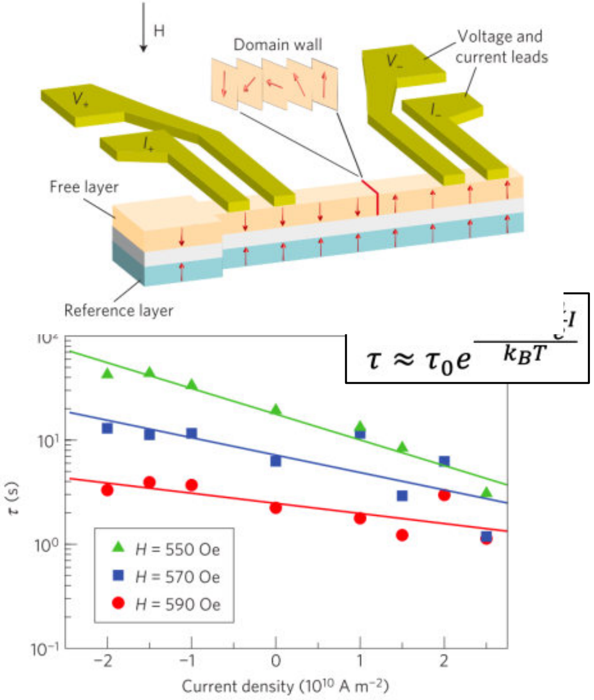


Thomas, Nature 443, 197 (2006)

Experimental observations

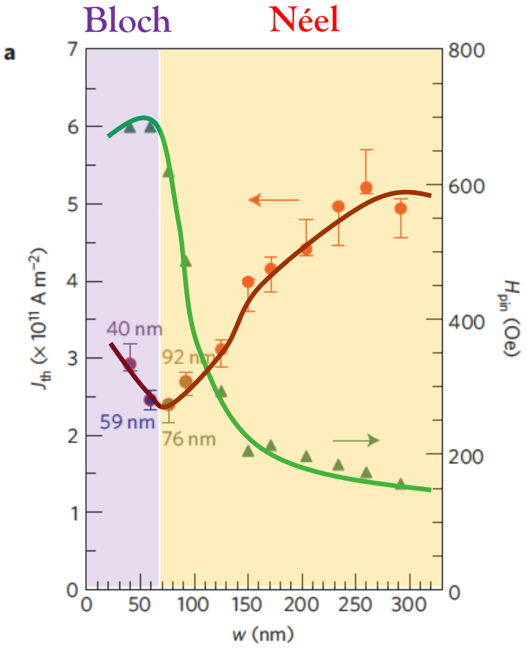
Perpendicularly magnetized domain walls

Extrinsic pinning

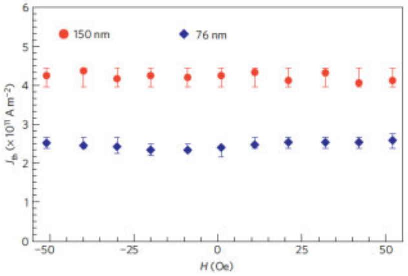


Burrowes, Nature Physics 6, 17 (2010)

Intrinsic pinning



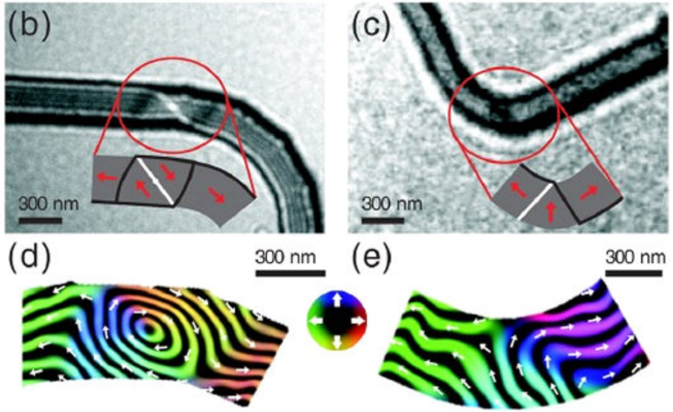
$$b_J > \left|\frac{\gamma_0 \Delta H_K}{2}\right|$$

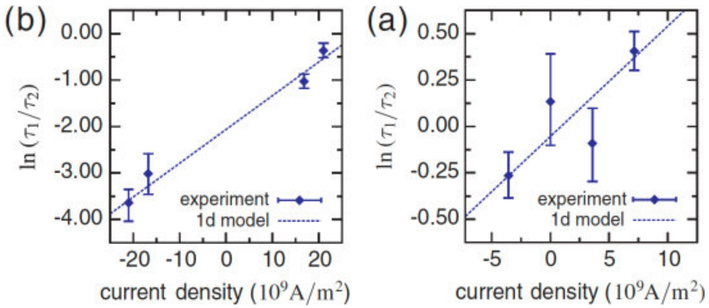


Koyama, Nature Materials 10, 194 (2011)

Experimental observations

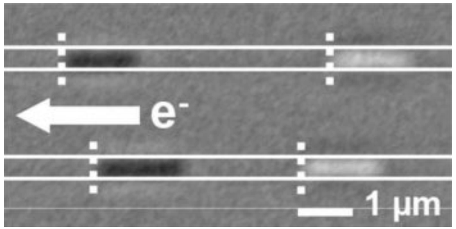
Py: Enhanced nonadiabaticity in vortices



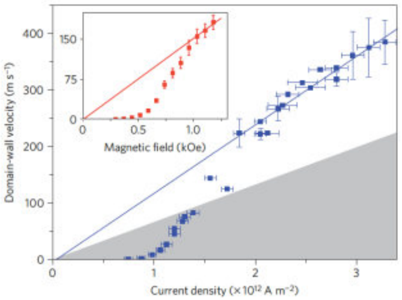


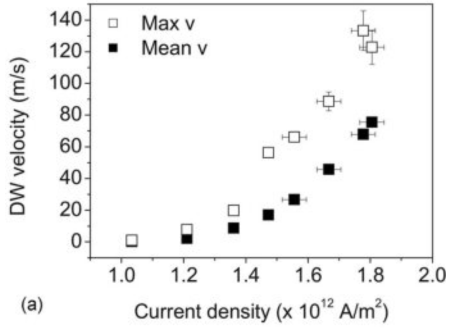
Heyne, Physical Review Letters 105, 056601 (2010)

Pt/Co: Giant negative mobility



Moore, Applied Physics Letters 93, 262504 (2008)
Moore, Applied Physics Letters 95, 179902 (2009)





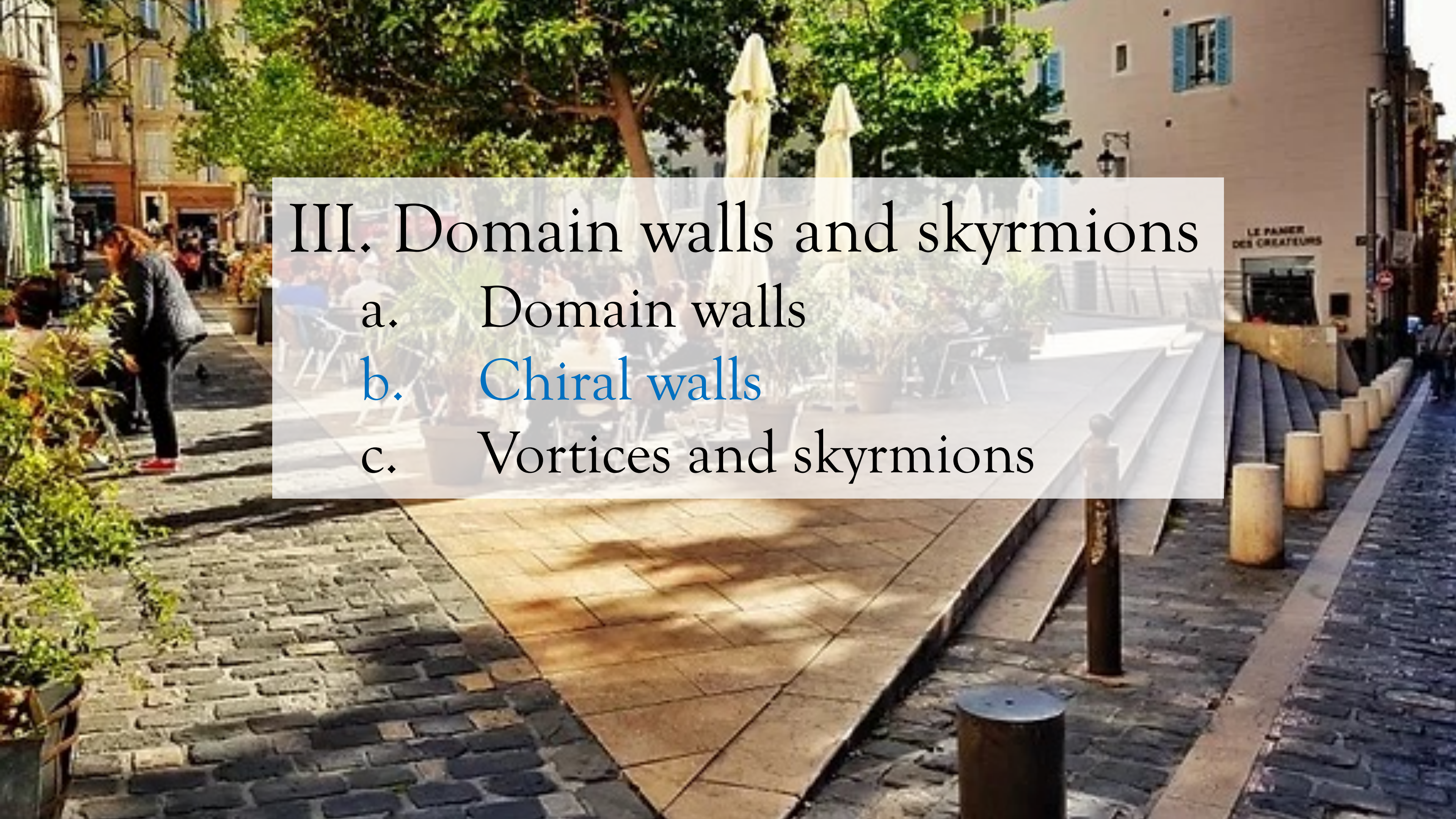
Miron, Nature Materials 10, 419 (2011)

III. Domain walls and skyrmions

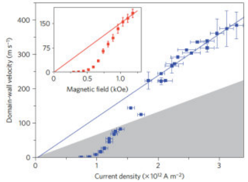
a. Domain walls

b. Chiral walls

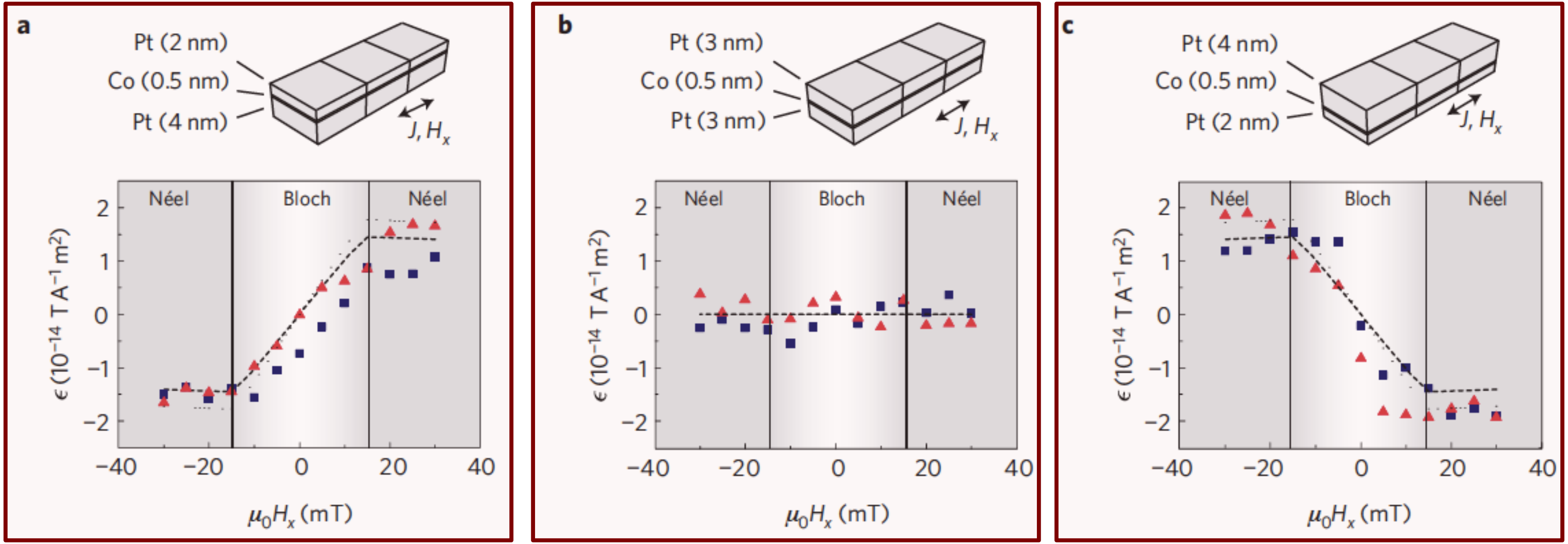
c. Vortices and skyrmions



Chiral domain walls


Miron, Nature Materials 10, 419 (2011)

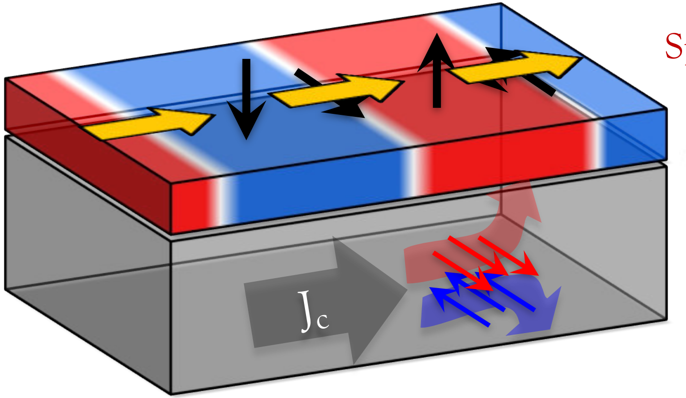
The domain wall flows along the electron direction
The domain wall velocity is much larger than usual
Inversion symmetry breaking seem to play a central role



Haazen, Nature Materials 12, 299 (2013)

Chiral domain walls

$$W_{DMI} = D\boldsymbol{m} \cdot ((\boldsymbol{z} \times \boldsymbol{\nabla}) \times \boldsymbol{m})$$



$$H_D = \frac{\pi D}{2\mu_0 M_s \Delta}$$

favors Néel walls

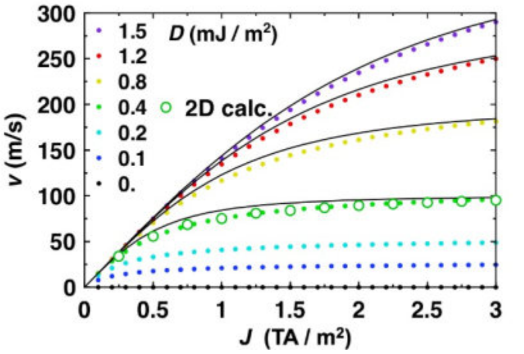
Spin Hall torque

$$\boldsymbol{\tau} = \frac{\hbar\theta_H}{2e}\boldsymbol{m} \times (\boldsymbol{z} \times \boldsymbol{j_c}) \times \boldsymbol{m}$$

Spin Hall efficiency

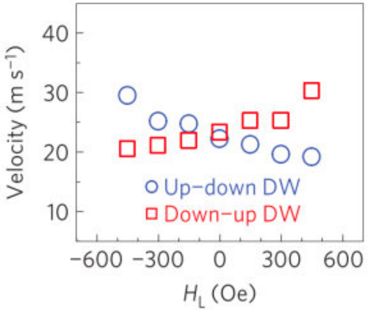
Current density

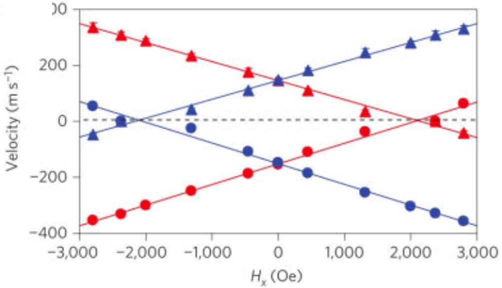
$$v = \frac{\gamma_0 \Delta H_D}{\sqrt{1 + (J_D/J)^2}} \qquad J_D = \frac{2\alpha t e D}{\hbar\theta_H \Delta}$$



Thiaville, EPL 100, 57002 (2012)

Experiments confirm the presence of an internal field



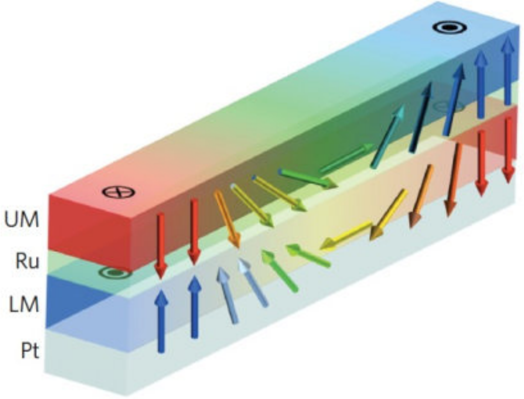


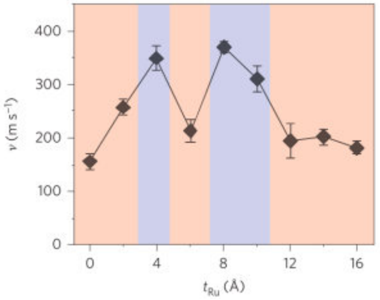
Emori, Nature Materials 12, 611 (2013)

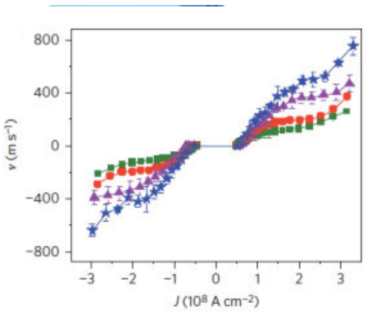
Ryu, Nature Nanotechnology 8, 527 (2013)

Chiral domain walls

Synthetic antiferromagnets







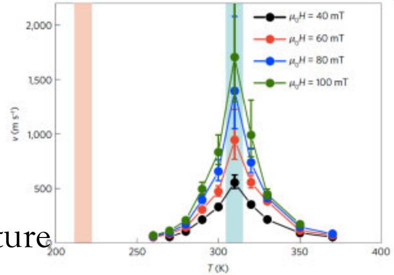
Yang, Nature Physics 10, 221 (2015)

Compensated ferrimagnets

Field-driven

GdFeCo

Maximum velocity at angular momentum compensation temperature

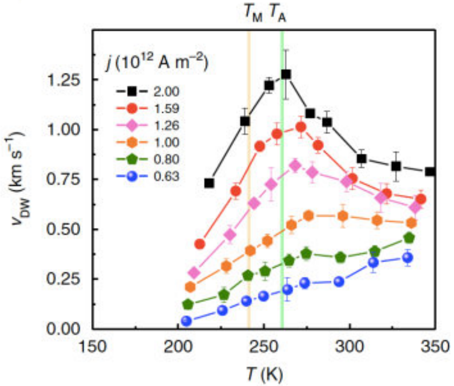


Kim, Nature Physics 16, 1187 (2017)

Current-driven

Pt/$Gd_{44}Co_{56}$

Same physics induces velocities up to 1.3km/s !



Caretta, Nature Nanotechnology 13, 1154 (2018)

III. Domain walls and skyrmions

a. Domain walls

b. Chiral walls

c. Vortices and skyrmions

Beyond one dimensional walls

Find a "Newton equation" for a rigid texture

$$\partial_t \boldsymbol{m} = \gamma_0 \boldsymbol{m} \times \partial_{\boldsymbol{m}} W + \alpha \boldsymbol{m} \times \partial_t \boldsymbol{m}$$

"Thermodynamical" force

"Mechanical" force

$$\boldsymbol{F} = \int d\Omega \boldsymbol{\nabla} W = \int d\Omega \boldsymbol{\nabla} m_i \partial_{m_i} W$$

$$\boldsymbol{\nabla} m_i \partial_{m_i} W = (\sin\theta / \gamma_0)[\boldsymbol{\nabla}\varphi(\boldsymbol{v}\cdot\boldsymbol{\nabla})\theta - \boldsymbol{\nabla}\theta(\boldsymbol{v}\cdot\boldsymbol{\nabla})\varphi] + (\alpha/\gamma_0)[\boldsymbol{\nabla}\theta(\boldsymbol{v}\cdot\boldsymbol{\nabla})\theta + \sin^2\theta\, \boldsymbol{\nabla}\varphi(\boldsymbol{v}\cdot\boldsymbol{\nabla})\varphi]$$

Hall effect!

$$\boldsymbol{F} + \boldsymbol{G} \times \boldsymbol{v} + \alpha \underline{D} \cdot \boldsymbol{v} = 0$$

Driving force
(field gradient or spin transfer torque)

Gyrotropic vector

$$\boldsymbol{G} = -\frac{1}{\gamma_0} \int d\Omega \sin\theta\, (\boldsymbol{\nabla}\theta \times \boldsymbol{\nabla}\varphi)$$

Dissipative tensor

$$\underline{D} = -\frac{1}{\gamma_0} \int d\Omega (\boldsymbol{\nabla}\theta \boldsymbol{\nabla}\theta + \sin^2\theta\, \boldsymbol{\nabla}\varphi \boldsymbol{\nabla}\varphi)$$

Thiele, Physical Review Letters 30, 230 (1973)

Current-driven vortex motion

$$\partial_t \boldsymbol{m} = \gamma_0 \boldsymbol{m} \times \partial_{\boldsymbol{m}} W + \alpha \boldsymbol{m} \times \partial_t \boldsymbol{m}$$

$$\boldsymbol{F} + \boldsymbol{G} \times \boldsymbol{v} + \alpha \underline{\mathcal{D}} \cdot \boldsymbol{v} = 0$$

Hall effect!

Gyrotropic vector

$$\boldsymbol{G} = -\frac{1}{\gamma_0} \int d\Omega \sin\theta \, (\boldsymbol{\nabla}\theta \times \boldsymbol{\nabla}\varphi)$$

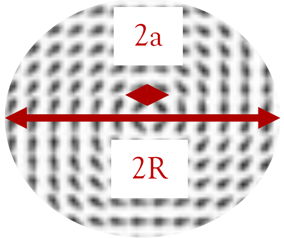
Dissipative tensor

$$\underline{\mathcal{D}} = -\frac{1}{\gamma_0} \int d\Omega (\boldsymbol{\nabla}\theta \boldsymbol{\nabla}\theta + \sin^2\theta \, \boldsymbol{\nabla}\varphi \boldsymbol{\nabla}\varphi)$$

Driving force

$$\boldsymbol{F} = \int d\Omega \boldsymbol{\nabla} W = \int d\Omega \boldsymbol{\nabla} m_i \partial_{m_i} W$$

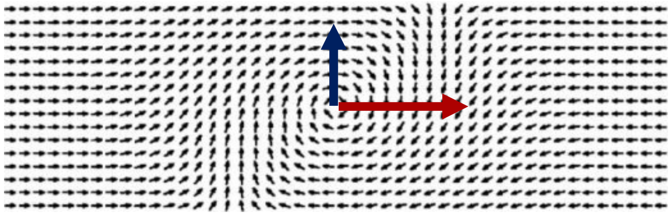
Thiele, Physical Review Letters 30, 230 (1973)



$$\boldsymbol{G} = -2\pi p \frac{M_s}{\gamma} \boldsymbol{z}$$

$$\underline{\mathcal{D}} = -\pi \frac{M_s}{\gamma} f\left(\frac{R}{a}\right) (\boldsymbol{x} \otimes \boldsymbol{x} + \boldsymbol{y} \otimes \boldsymbol{y})$$

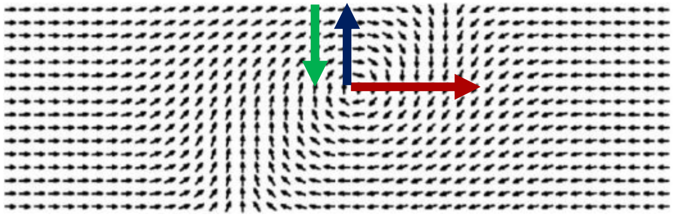
Free motion



$$v_x \approx -b_J$$

$$v_y \approx -\frac{1}{2} b_J p (\alpha - \beta) f\left(\frac{R}{a}\right)$$

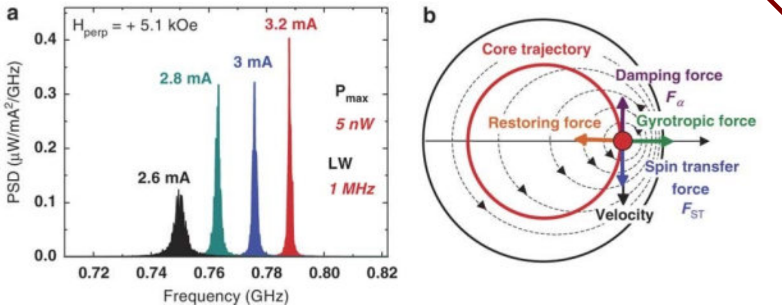
Hard walls



$$v_x \approx -\frac{\beta}{\alpha} b_J$$

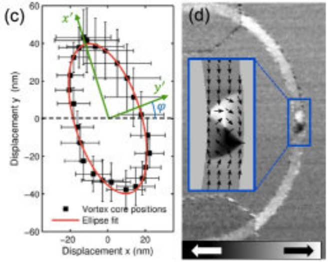
Vortex core dynamics

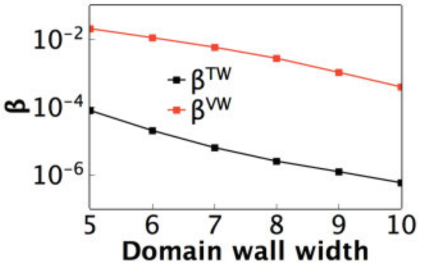
Current-driven vortex resonance



Dusseaux, Nature Communications 1, 8 (2010)

See also Kasai PRL 2006; Pribiag Nature Physics 2007

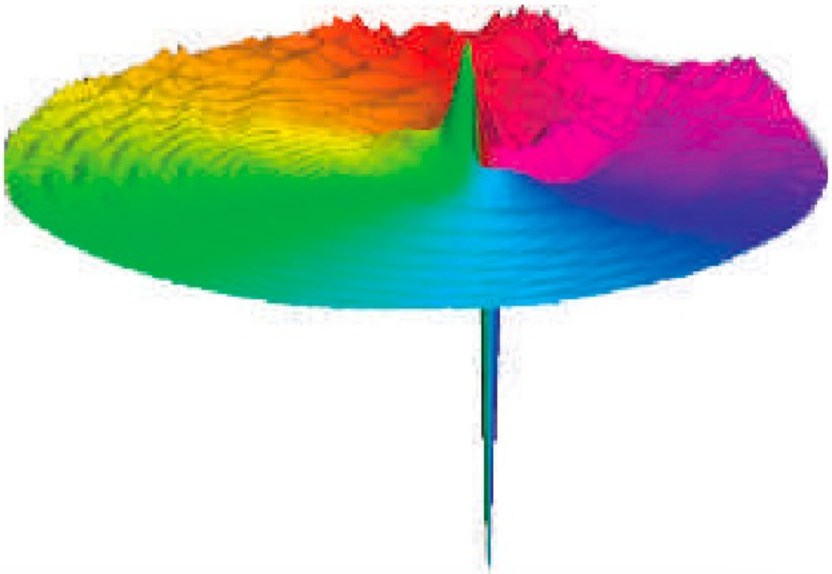




Enhanced non-adiabaticity due to vortex topology

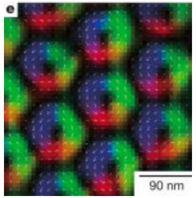
Bisig, Physical Review Letters 117, 277203(2016)

Current-driven vortex switching



Yamada, Nature Materials 6, 269 (2008)

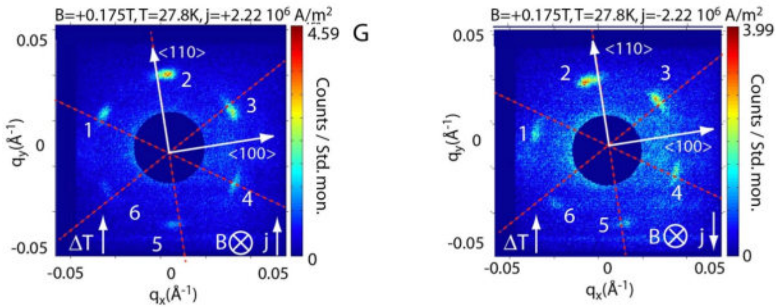
Skyrmion dynamics



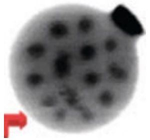
MnSi, T<30 K

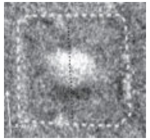
First observation of
stable skyrmion lattices
in bulk MnSi magnet

Yu Nature 465, 901 (2010)
Mühlbauer Science 323, 915 (2009)

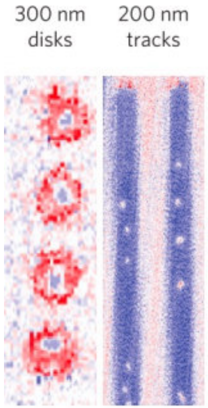


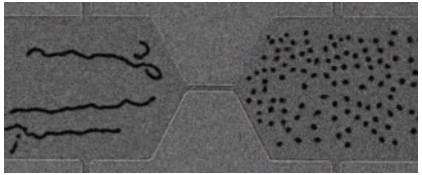
Jonietz Science 330, 1648 (2010)
Schultz Nature Physics 8, 301 (2012)





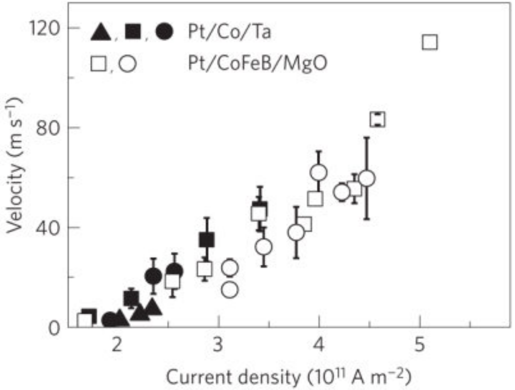
Pt/Co/Ta   Pt/Co/MgO



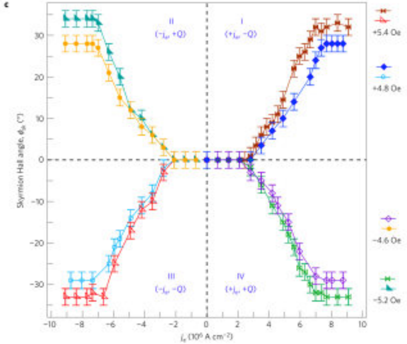


Ta/CoFeB/TaOx $(Ir/Co/Pt)_{10}$

Jiang Science 349, 283 (2015)
Chen Appl. Phys. Lett. 106, 242404 (2015)
Moreau-Luchaire Nature Nanotechnology 11, 444 (2016).
Boulle, Nature Nanotechnology 11, 449 (2016)
Woo Nature Materials 15, 501 (2016)



Woo Nature Materials 2016

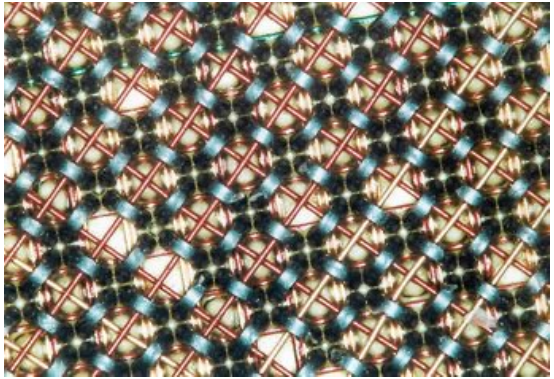


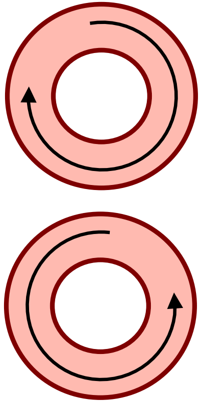
Jiang Nature Physics 13, 162 (2017)
Litzius, Nature Physics 13, 170 (2017)

BONUS!!
Spin torque devices

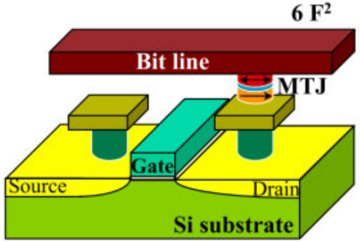
Magnetic random-access memories

IBM magnetic core memories

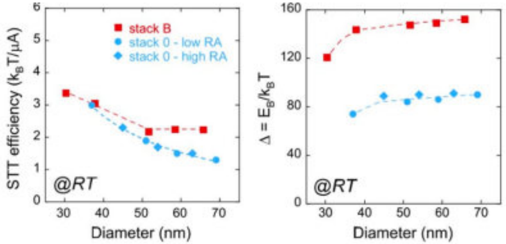




Spin torque-driven MRAM

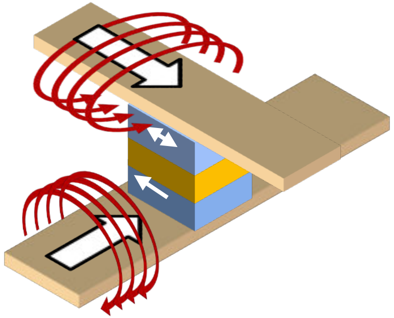


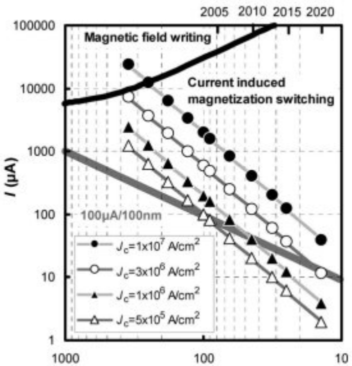
Apalkov Proc. IEEE 104, 1796 (2016)



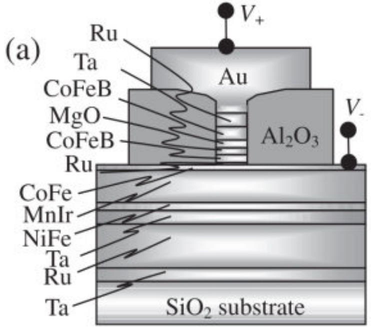
Thomas JAP 115, 172615. (2014)

Field-driven MRAM

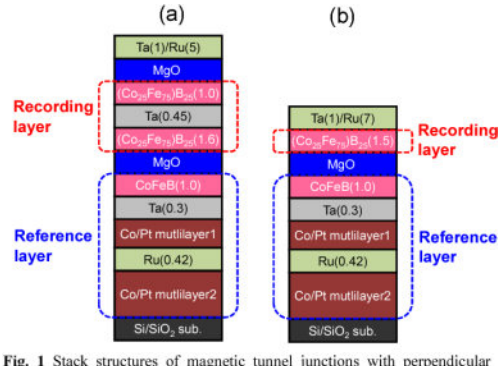




Ikeda IEEE Trans. Mag. 2007



Hayakawa JJAP 44, L587 (2005)

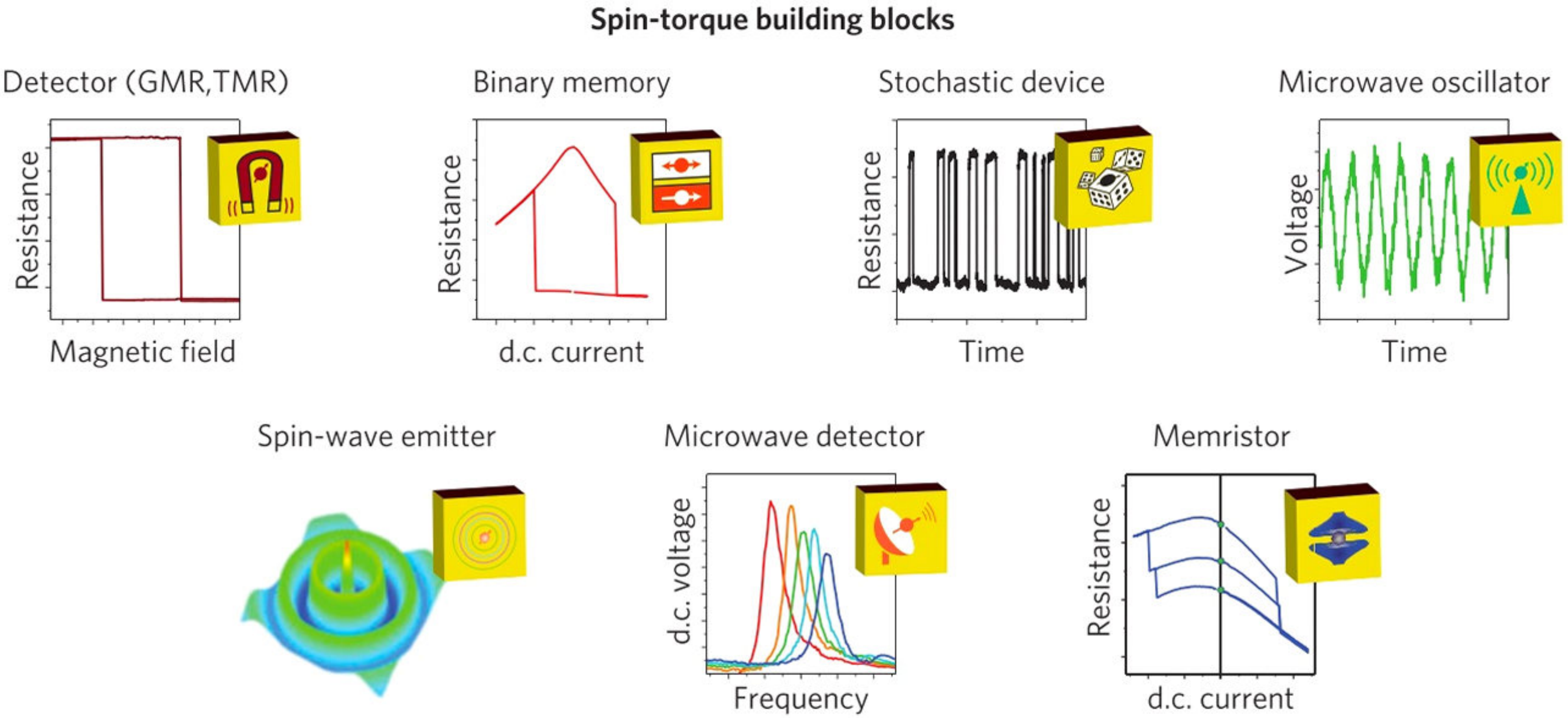


Ikeda IEDM 2014

Naganuma VLSI 2021

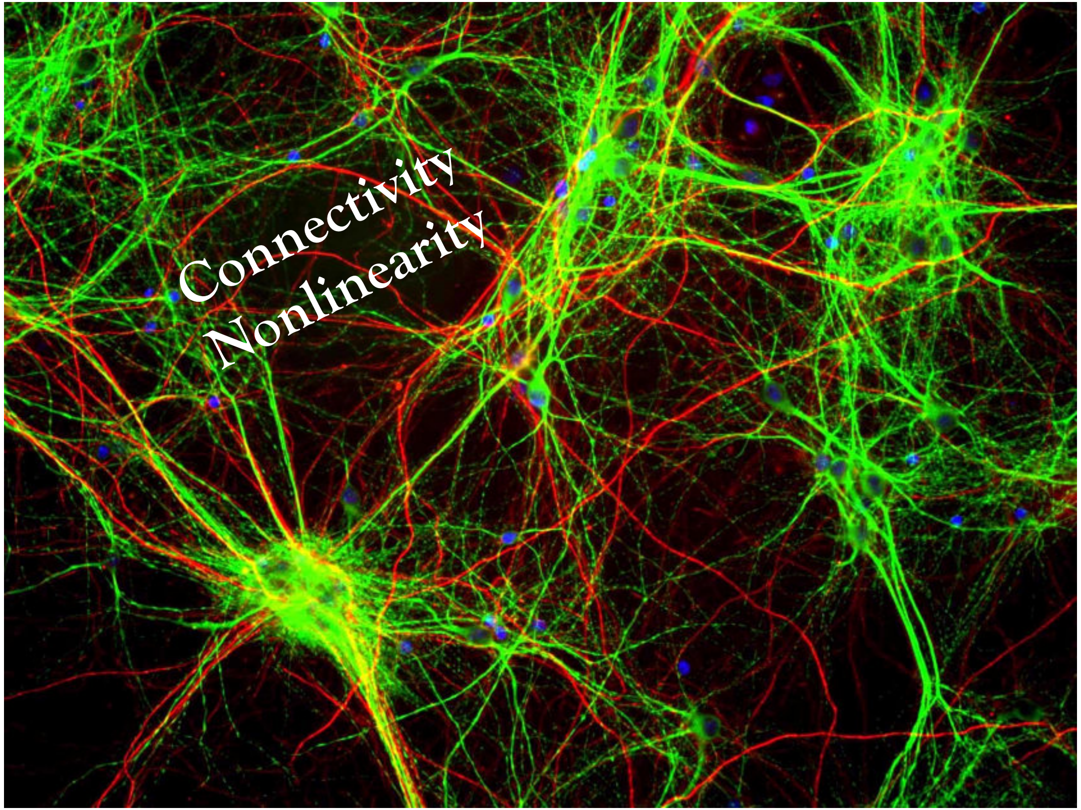
Thermal stability and critical switching current

The many opportunities of spin transfer torque



Locatelli et al., Nature Materials 13, 11 (2013)

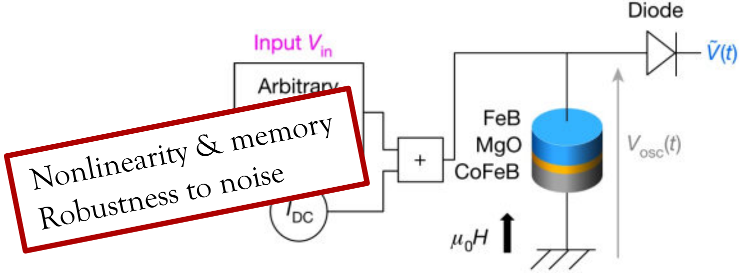
Nano-oscillators and neuromorphic computing



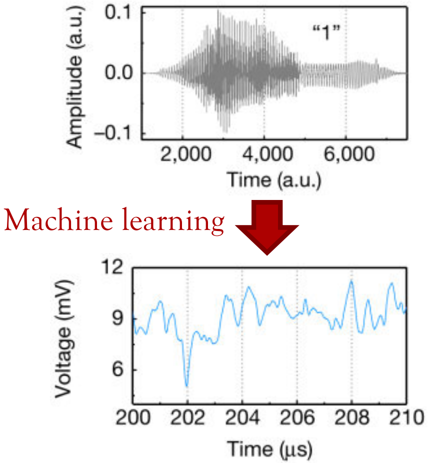
https://commons.wikimedia.org

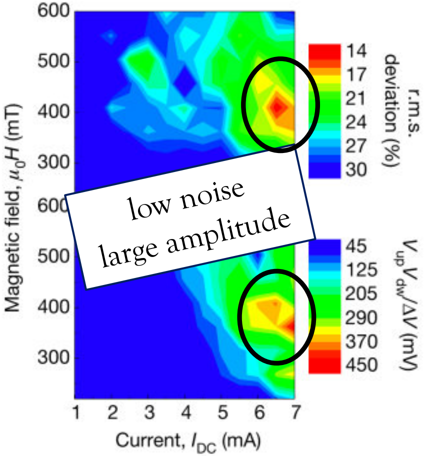
Nano-oscillators and neuromorphic computing

A single nanooscillator as a reservoir emulator



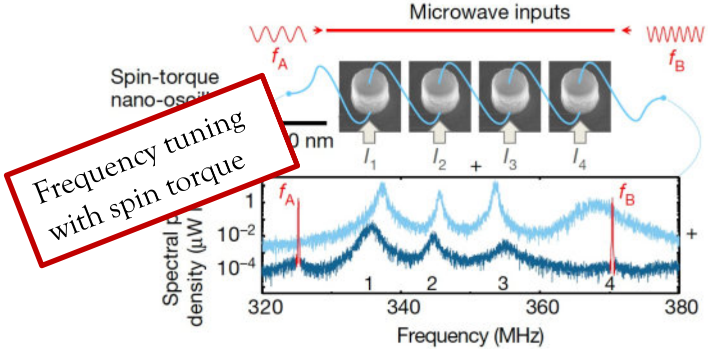
Neural network in time domain



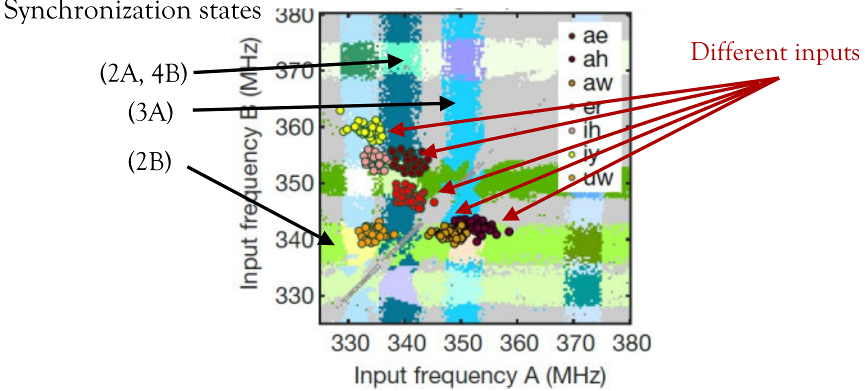


Torrejon et al., Nature 547, 428 (2017)

Coupled nanooscillators for vowel recognition



Synchronization map



Romera et al., Nature 563, 230 (2018)


That's all folks!
Hope you liked it!