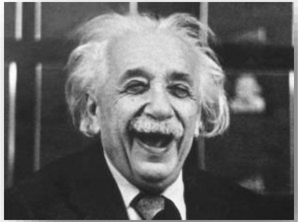
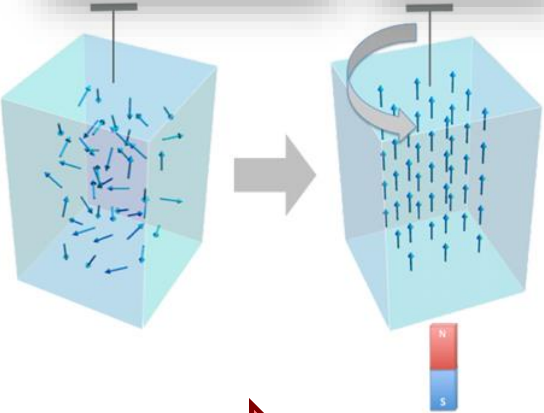
Spin Transfer Torque

by Aurélien Manchon
physiquemanchon.wixsite.com

The art of throwing spinning balls

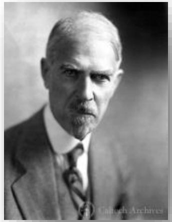
Einstein de Haas effect

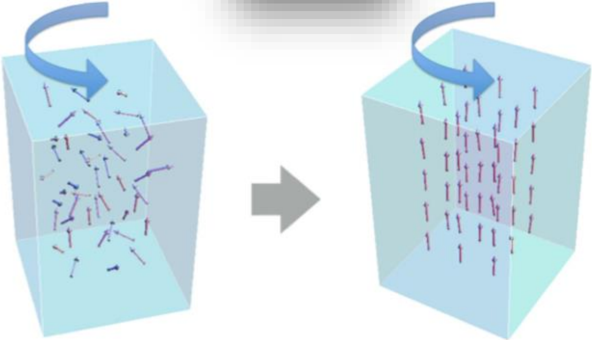




Magnetic field ⇒ Mechanical torque

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).

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The art of throwing spinning balls

Slonczewski's picture: angular momentum conservation

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

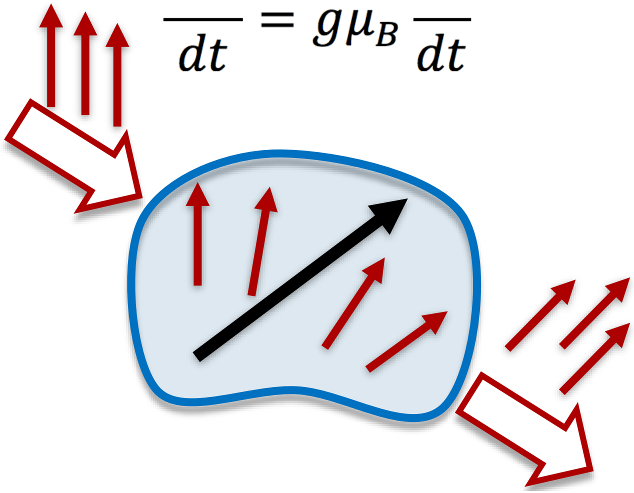
"Local" magnetization "conduction" spin

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

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**

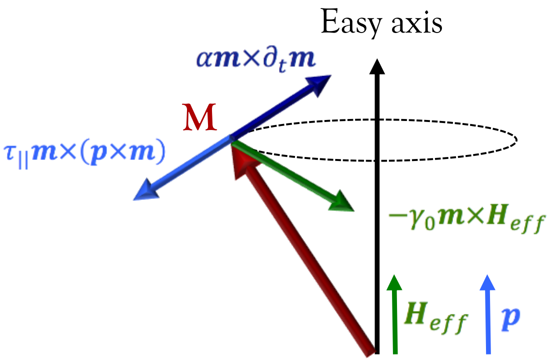
$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{T} = \int d\Omega \boldsymbol{m}\times\left[\left(\boldsymbol{J}_s^{in} - \boldsymbol{J}_s^{out}\right)\times\boldsymbol{m}\right]$$

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

The art of throwing spinning balls

Current-driven dynamics

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

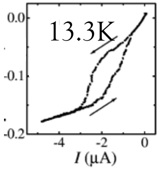


$\alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} > \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ M relaxes towards H_{eff}

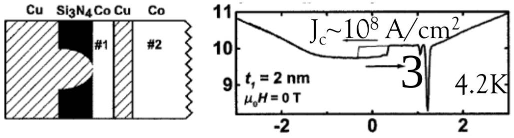
$\alpha\boldsymbol{m}\times\partial_t\boldsymbol{m} < \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$ M switches towards $-H_{eff}$

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

$La_{0.67}Sr_{0.33}MnO/SrTiO_3$
A~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)

I. Spin Transfer Torque
II. Current-driven dynamics
III. Spin-orbitronics

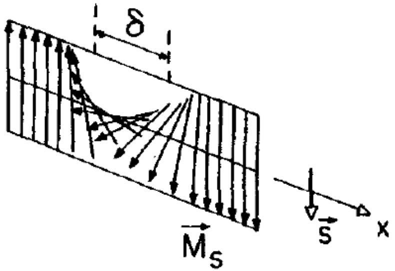
I. Spin Transfer Torque and Spin Pumping

a. Transfer of angular momentum

b. Spin pumping

Principle of spin transfer torque

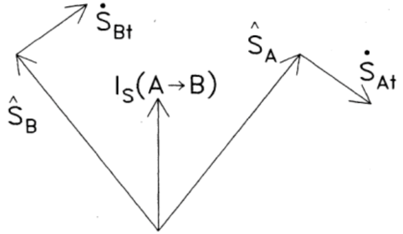
Spin torque in magnetic domain walls



"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

$$\boldsymbol{J}_s \sim \boldsymbol{S}_A + \boldsymbol{S}_B$$

$$\partial_t S \partial_t \boldsymbol{S}_A = -\boldsymbol{S}_A \times (\boldsymbol{J}_s \times \boldsymbol{S}_A)'_A]$$

$$\partial_t \boldsymbol{S}_A \propto \boldsymbol{S}_A \times (\boldsymbol{S}_A \times \boldsymbol{S}_B)$$

Slonczewski, Physical Review B39, 6995 (1989)

Spin dephasing and spin current absorption (Tutorial)

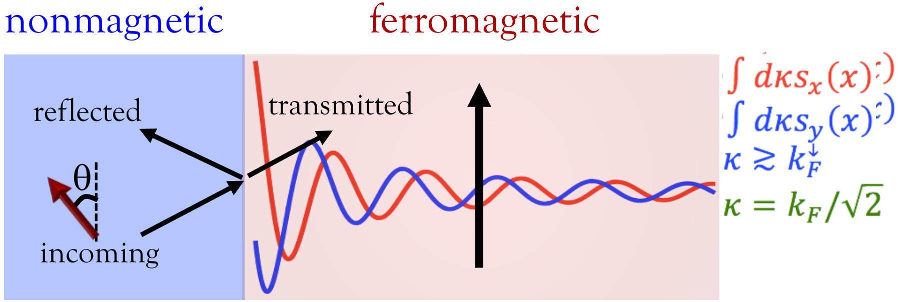
Quantum mechanical model

Wave function for a given spin σ

$$\psi_\sigma^N = \left[e^{ik_x x} + r_\sigma e^{-ik_x x}\right]e^{i\boldsymbol{\kappa}\cdot\boldsymbol{\rho}}$$
$$\psi_\sigma^F = t_\sigma e^{i(k_x^\sigma x + \boldsymbol{\kappa}\cdot\boldsymbol{\rho})}$$

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

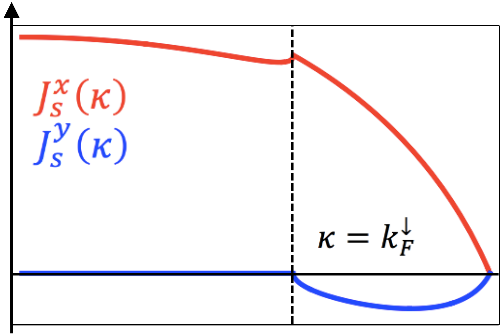
$$\boldsymbol{T} = -\boldsymbol{m}\times\left(\int d\Omega[\boldsymbol{\nabla}\cdot\boldsymbol{J}_s]\times\boldsymbol{m}\right) = \frac{\mu_B}{dM_s}J_s^\perp|_{\text{interface}}$$

In metals, the spin torque is mostly "dampinglike"

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

magnetization

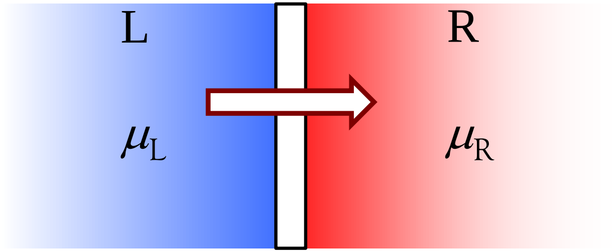
polarization



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

The concept of spin mixing conductance

Basics of circuit theory

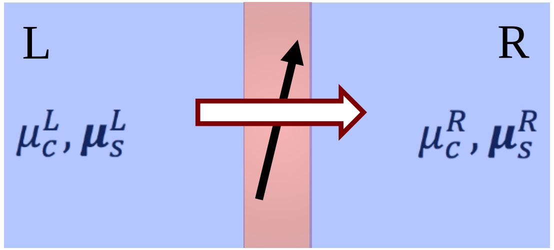


$$J_p = g(\mu_L - \mu_R)$$

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

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

Generalization of Ohm's law



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

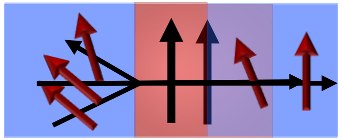
- This relation establishes a direction connection between the spin current and the spin accumulation
- All the spin physics (spin precession, relaxation, dephasing, scattering, magnetic texture etc.) is contained in just two coefficients

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

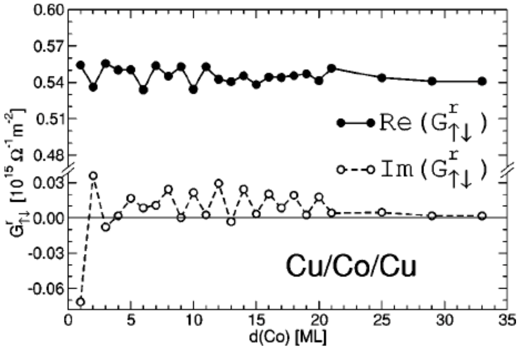
The concept of spin mixing conductance

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

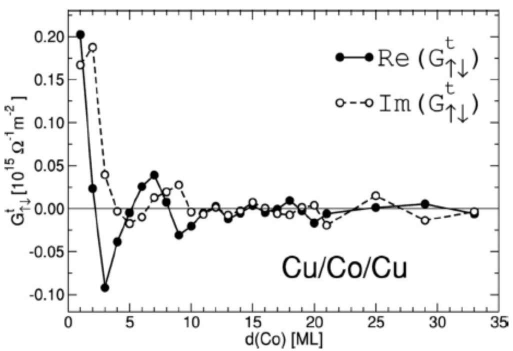
$$g_r^{\uparrow\downarrow} = \frac{e^2}{Ah}\sum_{nm}(\delta_{nm} - r_{nm}^{\uparrow}r_{nm}^{\downarrow *})$$
$$g_t^{\uparrow\downarrow} = \frac{e^2}{Ah}\sum_{nm} t'^{\uparrow}_{nm}t'^{\downarrow *}_{nm}$$



Reflected mixing conductance



Transmitted mixing conductance

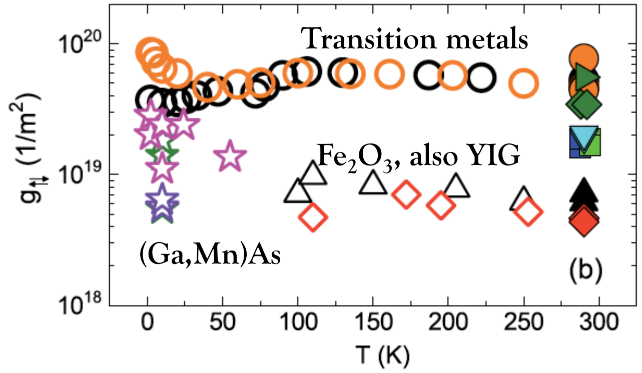


$$\mathrm{Re}[g_r^{\uparrow\downarrow}] \sim \frac{e^2}{Ah} \sim 0.5\times10^{15}\Omega^{-1}\cdot m^{-2}$$
$$\mathrm{Im}[g_r^{\uparrow\downarrow}] \sim 0$$
$$\mathrm{Re}[g_t^{\uparrow\downarrow}] \sim \mathrm{Im}[g_t^{\uparrow\downarrow}] \sim e^{-d/\lambda_\varphi}$$

$$\Rightarrow \quad J_{s,\perp}^{L} = 2\mathrm{Re}g_r^{\uparrow\downarrow}\boldsymbol{m}\times(\boldsymbol{\mu}_s^{L}\times\boldsymbol{m})$$
$$J_{s\perp}^{R} \approx 0$$

Zwierzycki, Physical Review B 71, 064420 (2005)

Reflected mixing conductance of various materials



Czeschka, Physical Review Letters 107, 046601 (2011)

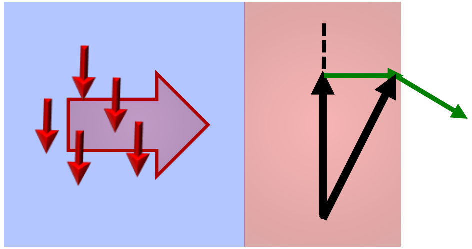
I. Spin Transfer Torque and Spin Pumping

a. Transfer of angular momentum

b. Spin pumping

Spin transfer torque and spin pumping

Spin transfer torque



Spin current

Torque on M

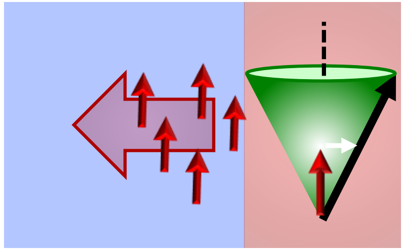
Magnetization dynamics

Spin current

Torque on s

Magnetization dynamics

Spin pumping



Onsager reciprocity


L. Onsager

Free energy

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

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

Generalized current Thermodynamics force

Anomalous Hall effect

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

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

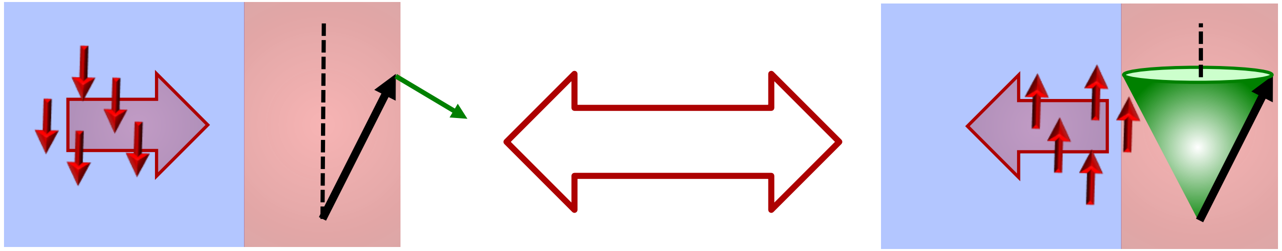
-1 if ξ_i is antisymmetric under time reversal

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

Onsager reciprocity

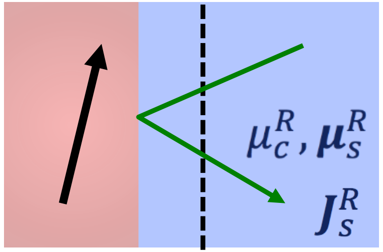
Spin transfer torque

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

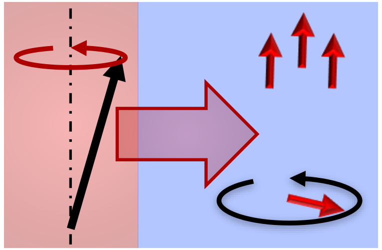
$$\mathcal{L}_{sm}^{ij}(\boldsymbol{m}) = \mathcal{L}_{ms}^{ji}(-\boldsymbol{m})$$

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

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)

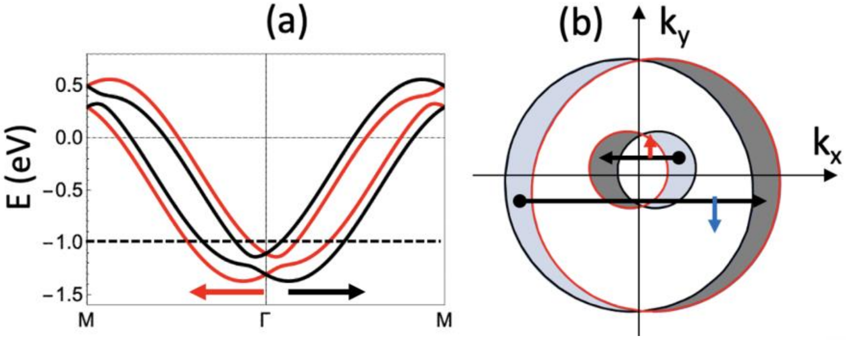
Consider a precessing magnetization

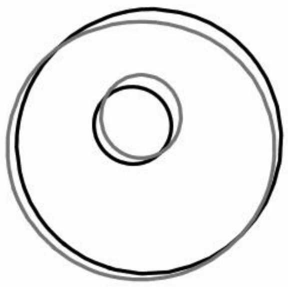
$$\boldsymbol{m} = \cos\theta\,\boldsymbol{z} + \sin\theta\,(\cos\omega t\,\boldsymbol{x} + \sin\omega t\,\boldsymbol{y})$$

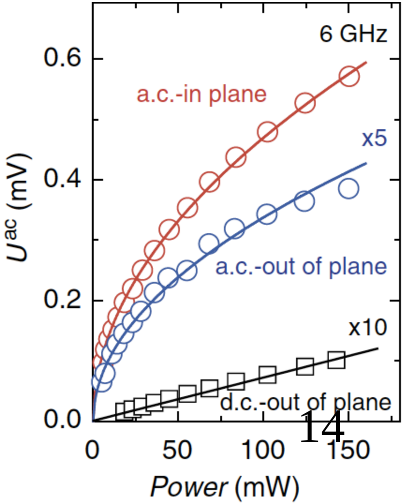
$$\frac{\hbar}{2}\boldsymbol{J}_s^{dc} = \frac{\hbar\omega}{4\pi}\mathrm{Re}\tilde{g}_r^{\uparrow\downarrow}\sin^2\theta\,\boldsymbol{z}$$

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

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

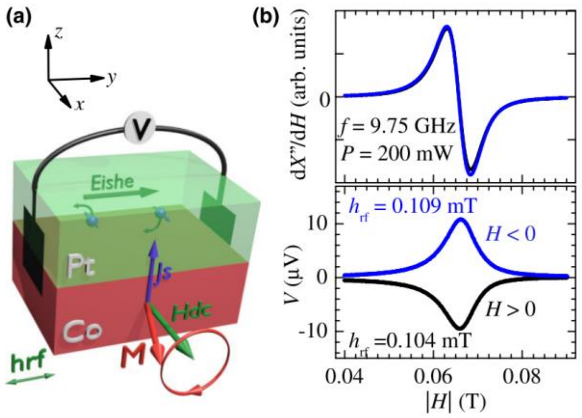




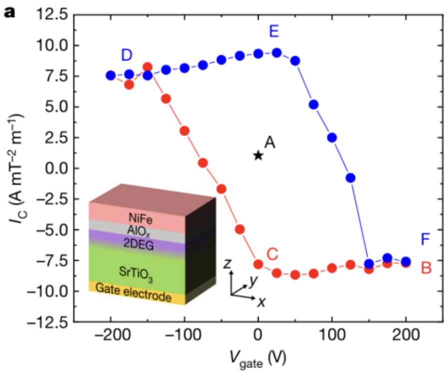


Wei et al., Nature Communications 5, 3768 (2014)

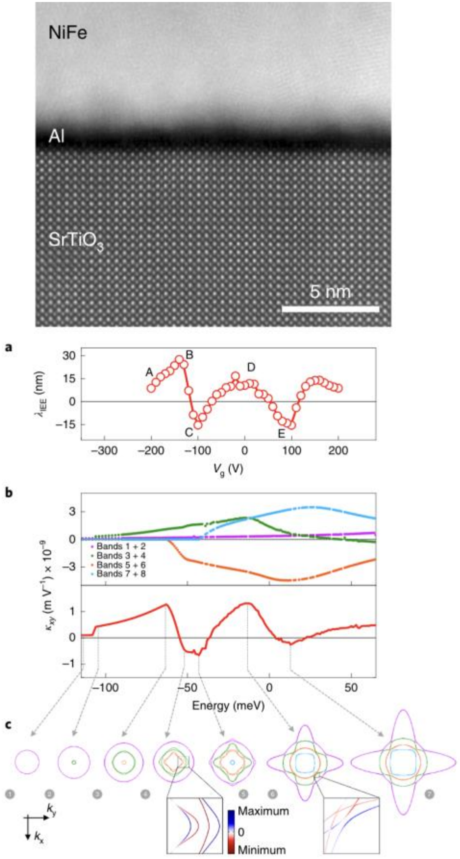
Some experiments on charge pumping



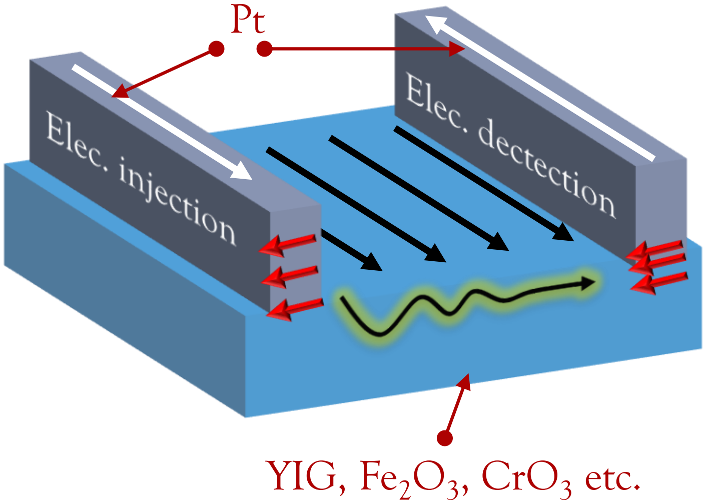
Saitoh et al., APL 88, 182509 (2006)

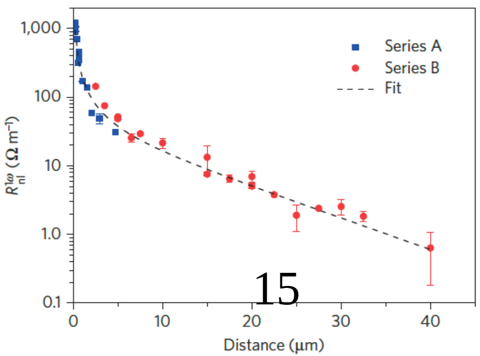


Noel et al., Nature 580, 483 (2020)



Vaz et al., Nature Materials 18, 1187 (2019)



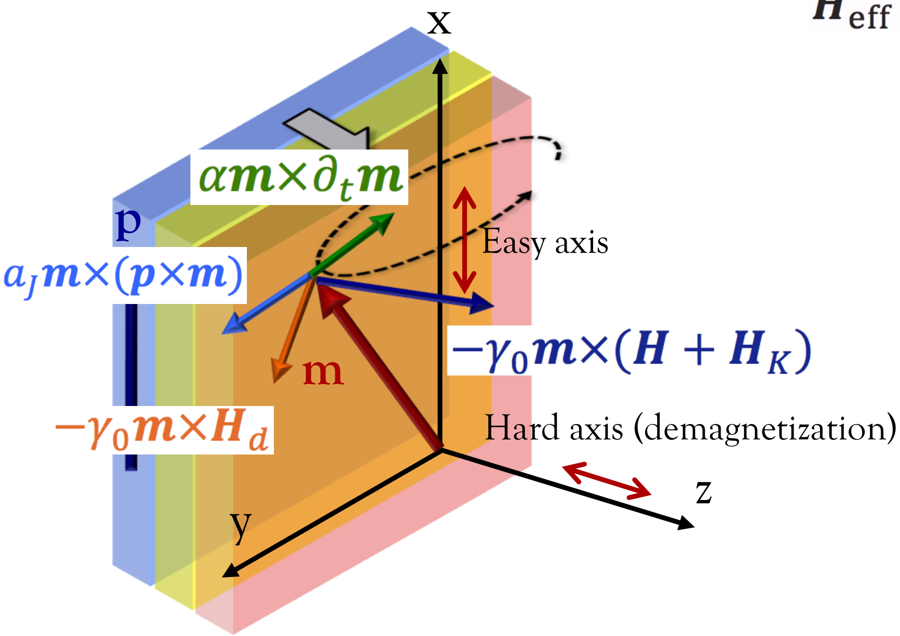


Cornelissen, Nat. Physics 11, 1022 (2015)

II. Current-driven magnetization dynamics

a. Switching
b. Self-sustained oscillations
c. Domain wall motion

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

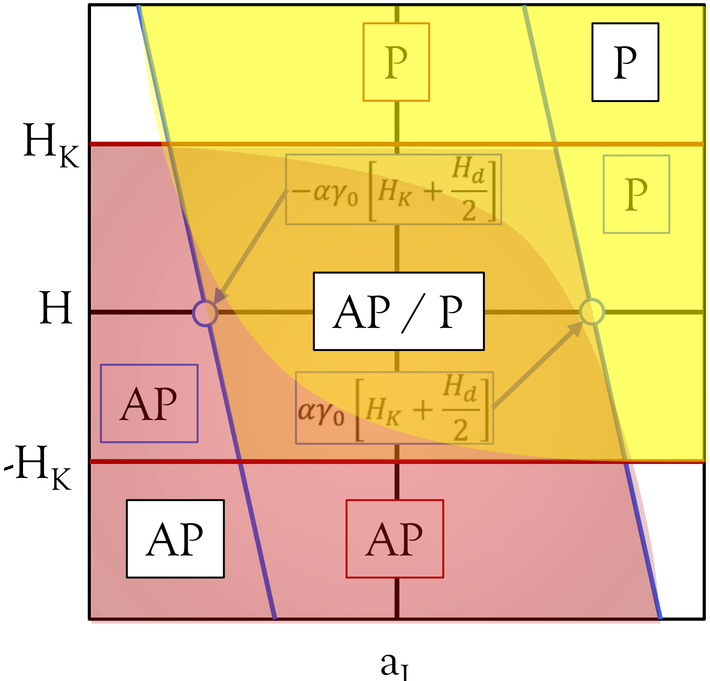
$$m_x = 1, \text{Im}\omega > 0 \Rightarrow a_J < -\alpha\gamma_0 \left[H + H_K + \frac{H_d}{2}\right]$$

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

Stability diagram and critical switching current

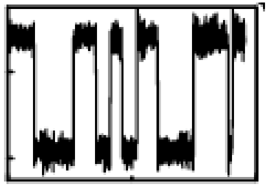
$$P \rightarrow AP \Rightarrow a_J < -\alpha\gamma_0 \left[H + H_K + \frac{H_d}{2}\right]$$

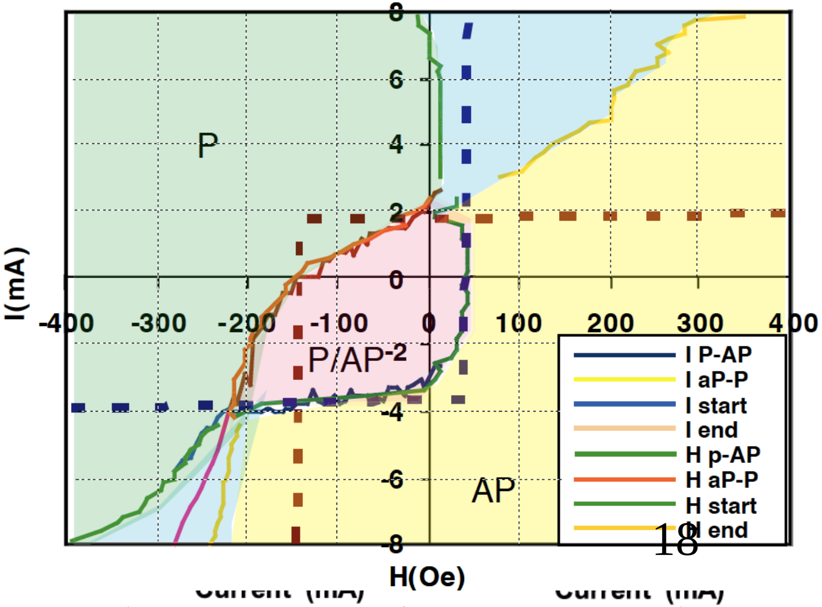
$$AP \rightarrow P \Rightarrow a_J > \alpha\gamma_0 \left[-H + H_K + \frac{H_d}{2}\right]$$



Thermal activation

Resistance fluctuation
due to superparamagnetism



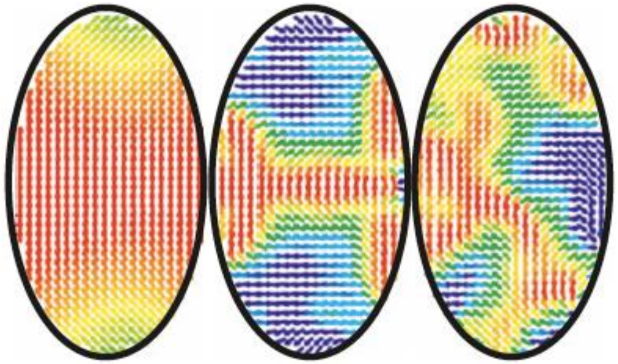


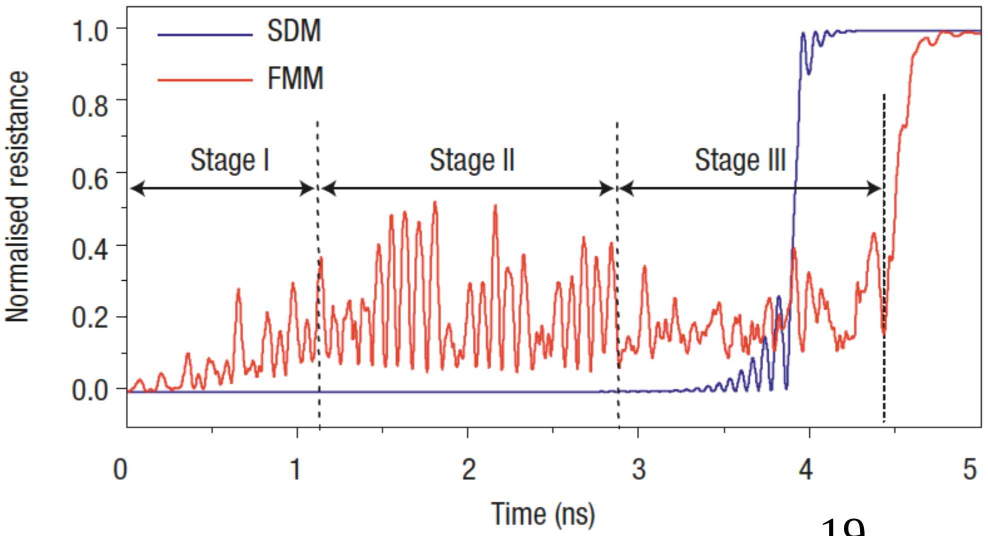
Deac, Journal of Magnetism and Magnetic Materials 290, 42 (2005)

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)

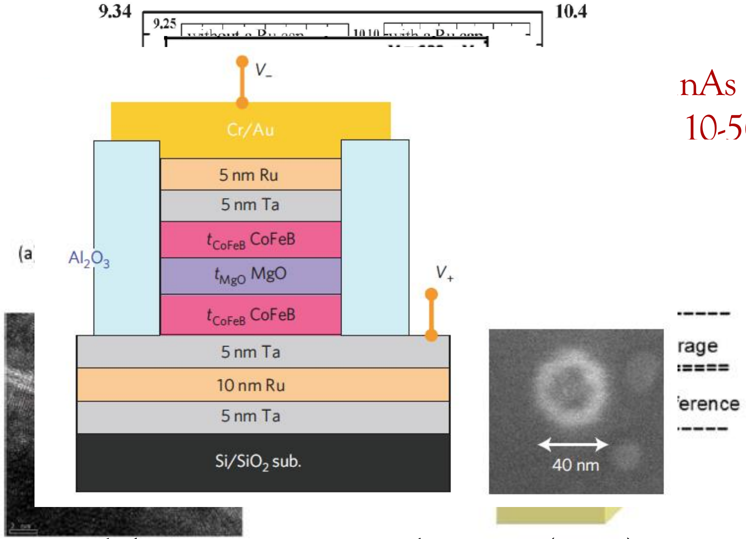
Strategies to optimize the critical switching current

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: $10^6 - 10^7$ A/cm^2

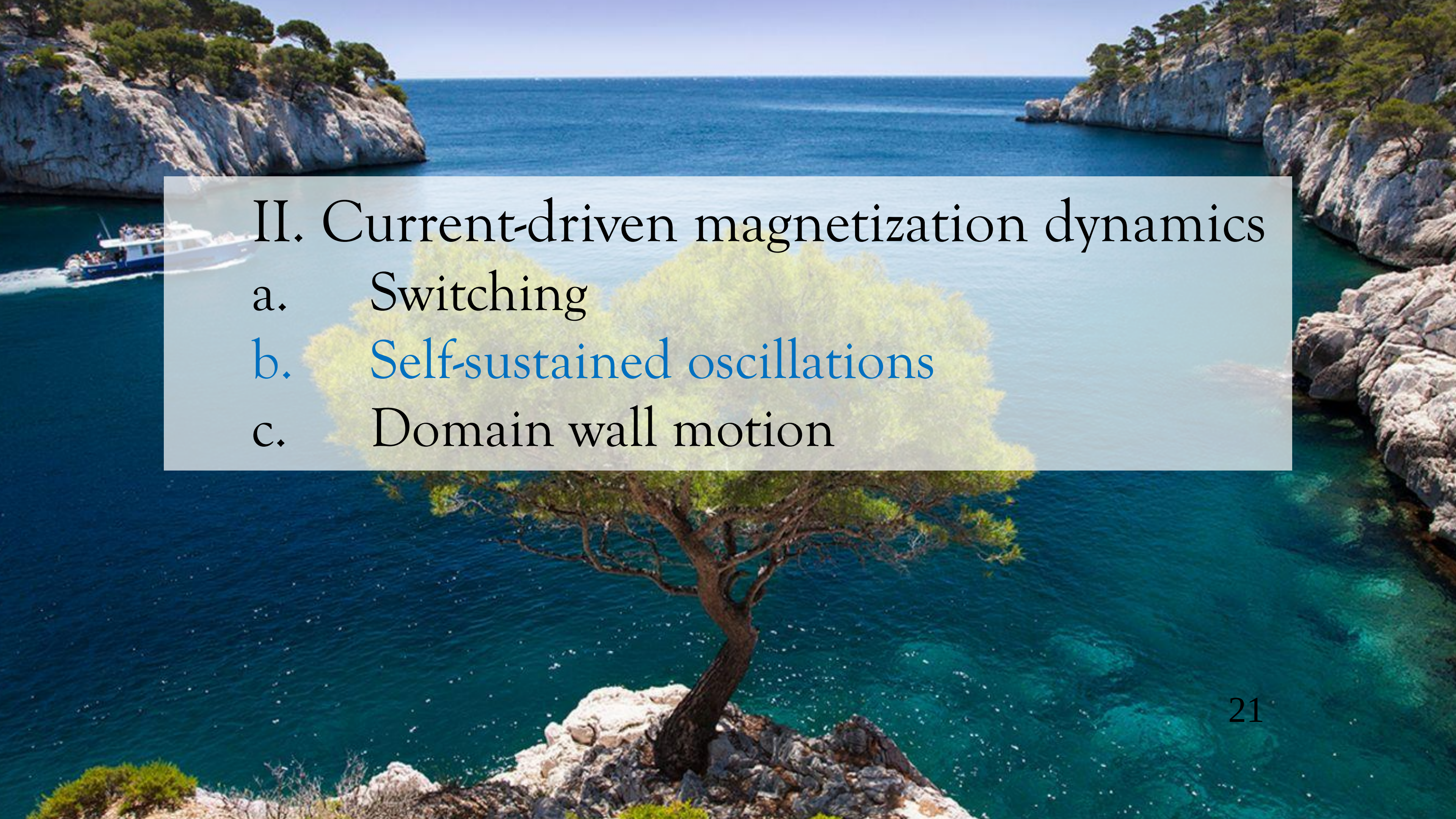
Ikeda, Nature Materials 5, 210 (2006)

Ounadjela, J ... (1988)

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

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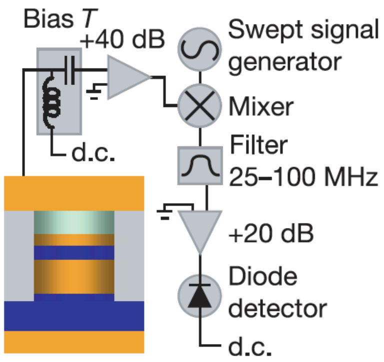
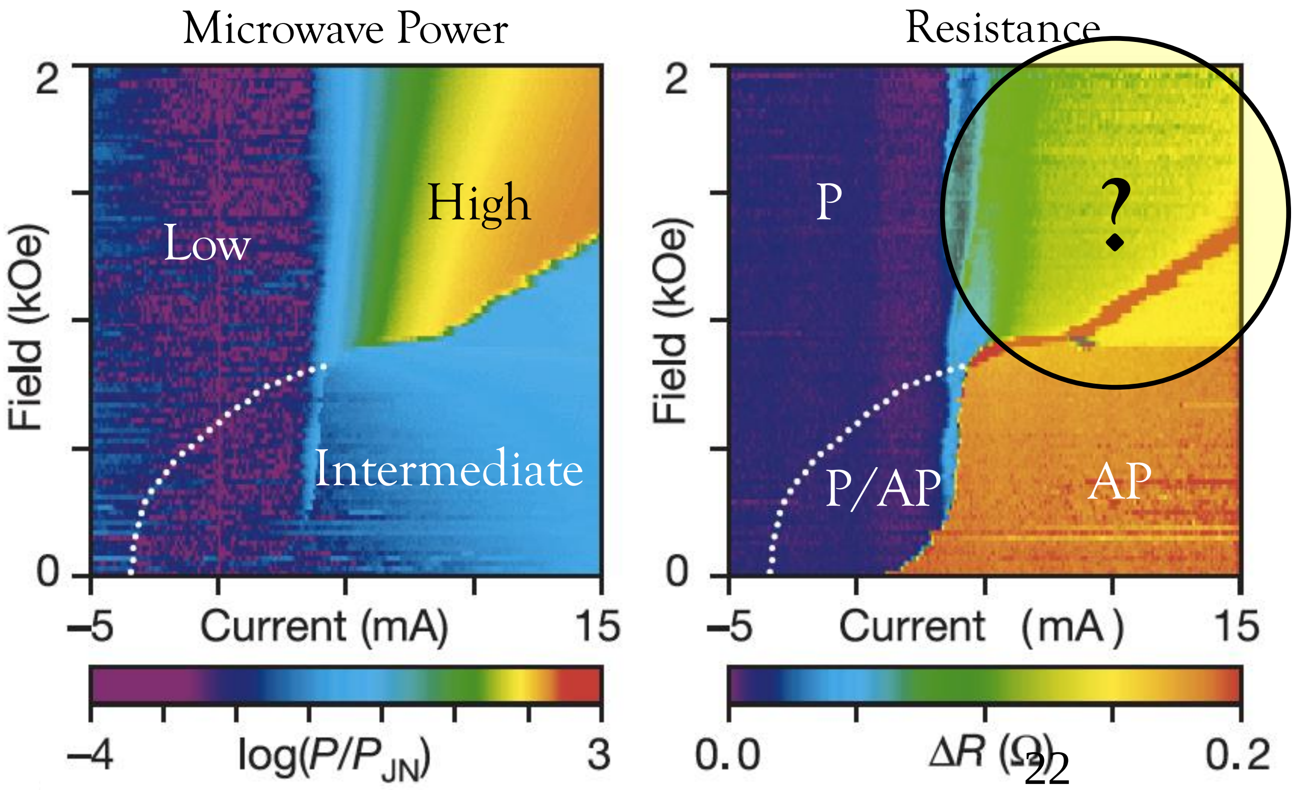
Beyond current-driven switching

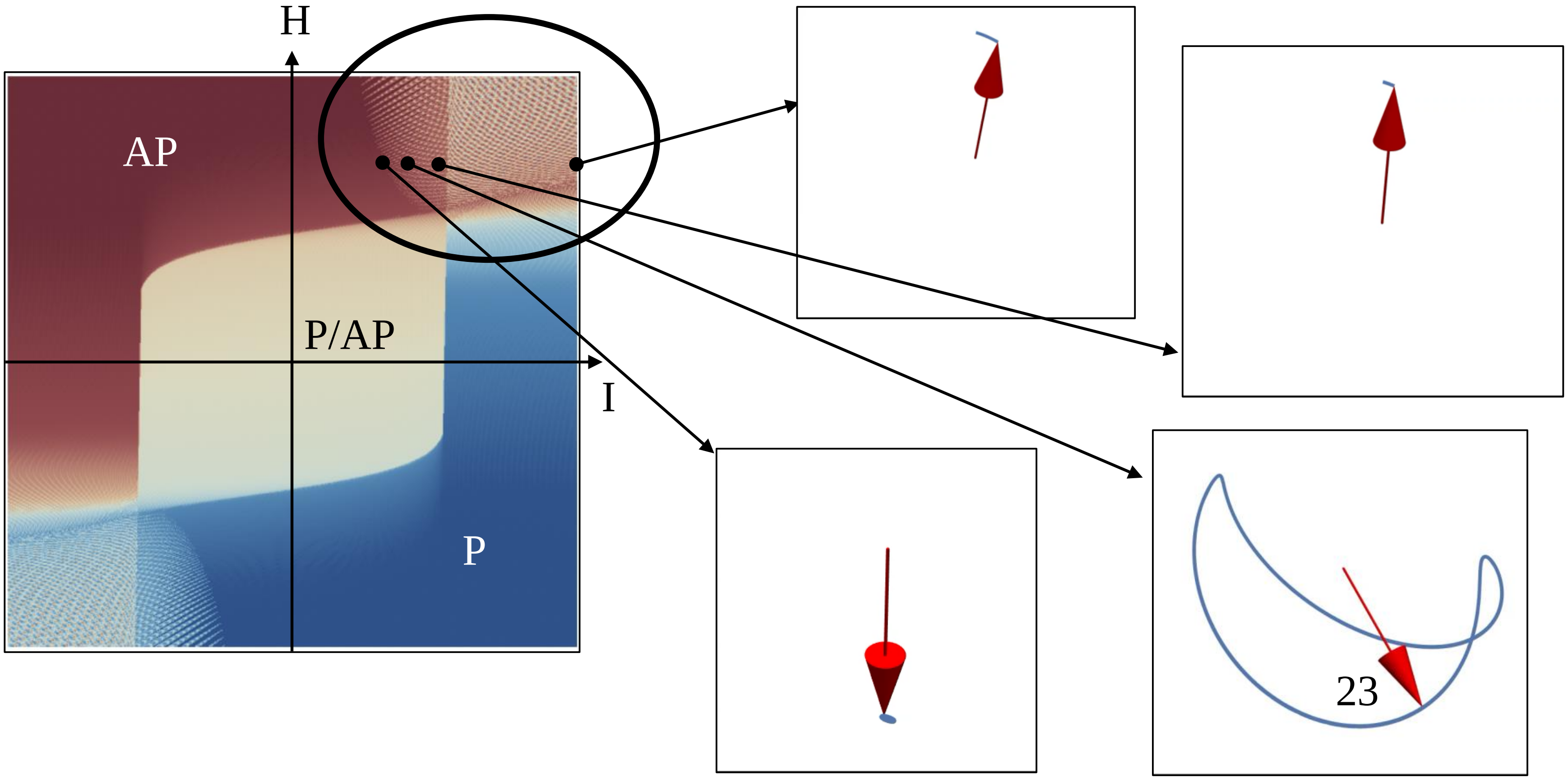
Co(40)/Cu(3)/Co(10)



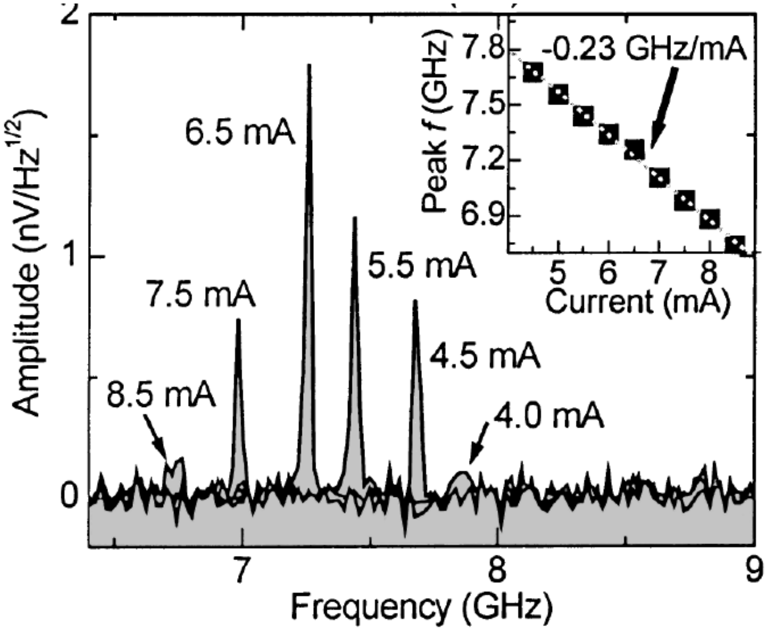


Kiselev, Nature 425, 380 (2003)

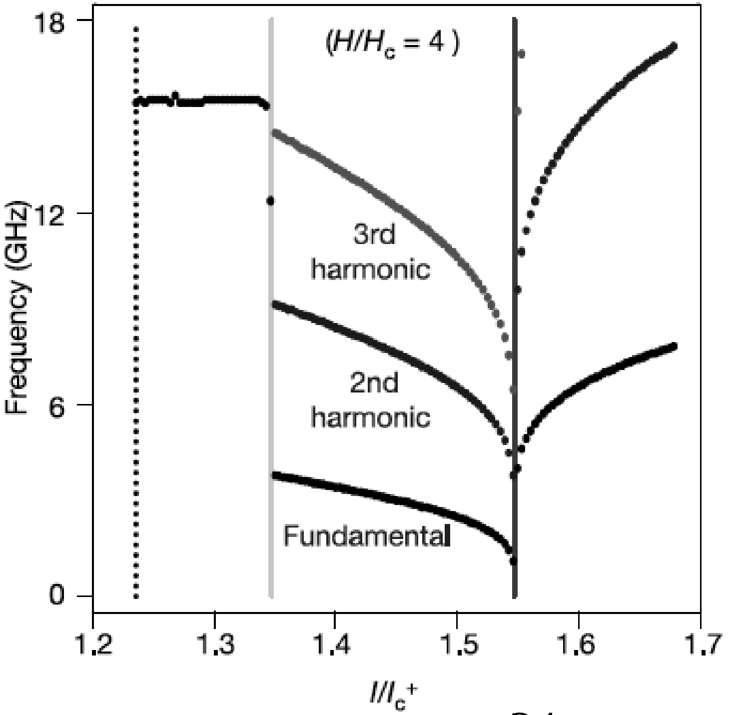
Current-driven self-oscillations



Current-driven self-oscillations



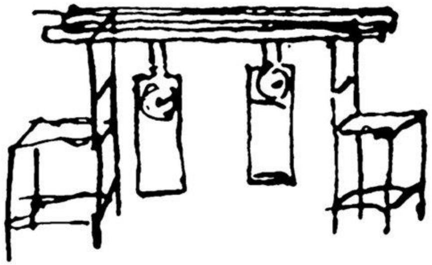
Rippard et al., Physical Review Letters 92, 027201 (2004)
J.V. Kim, *Spin-Torque Oscillators*, in Solid State Physics 63 (2012)



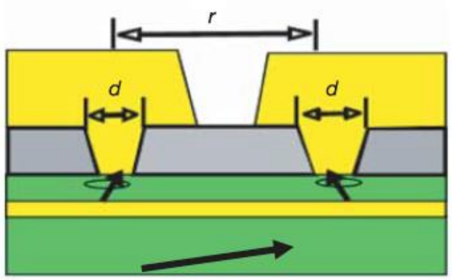
Kiselev et al., Nature 425, 380 (2003)

Current-driven self-oscillations

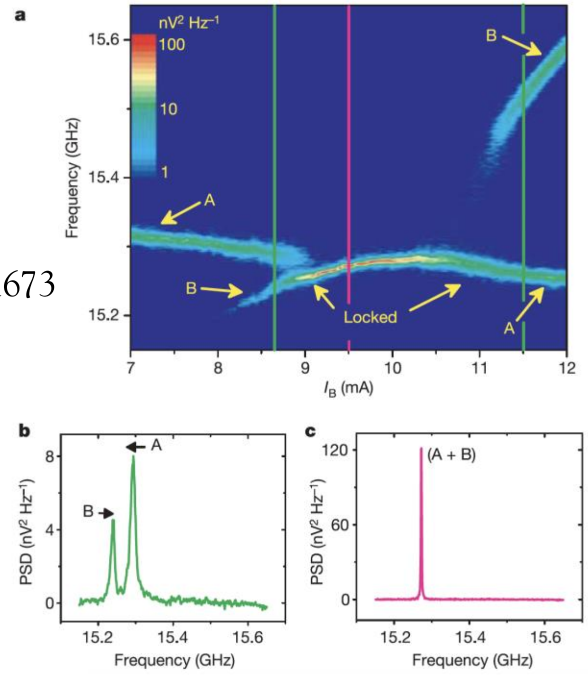
Synchronization between nano-oscillators

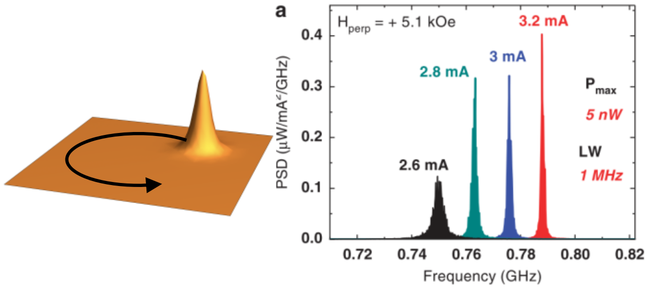


Hyungens, *Horologium Oscillatorium*, 1673

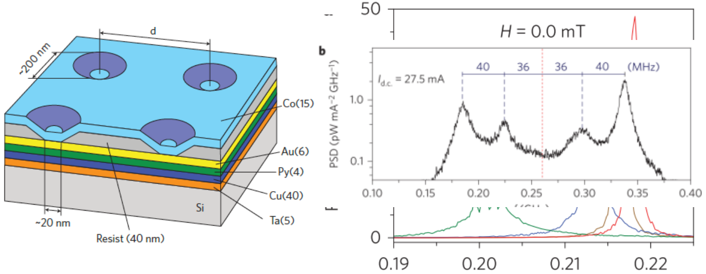


Mancoff, Nature 437, 393 (2005)
Kaka, Nature 437, 389 (2005)





Dussaux, Nature Comm. 10, 1038 (2010)



Ruotolo, Nature Nanotechnology 4, 528 (2009)

II. Current-driven magnetization dynamics

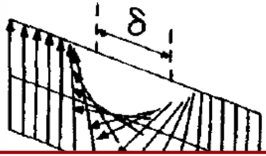
a. Switching

b. Self-sustained oscillations

c. Domain wall motion

Current-driven magnetic domain wall motion

Spin torque in magnetic domain walls



L. Ber

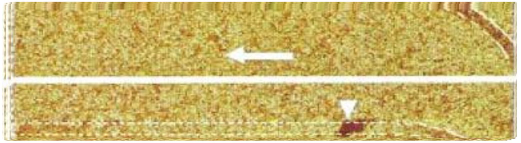
“As ar
follow
magnetization $\mathbf{M}_s$.”

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

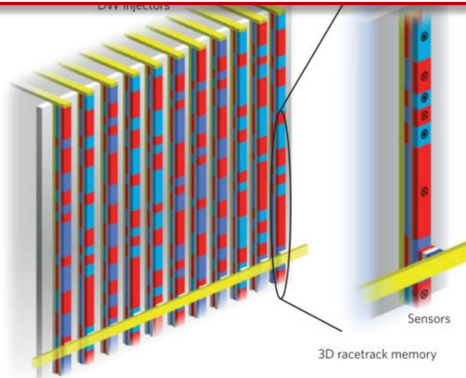
$$H_{ex} = \frac{1}{\delta}\frac{P\hbar}{eM_s}J_c$$

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)



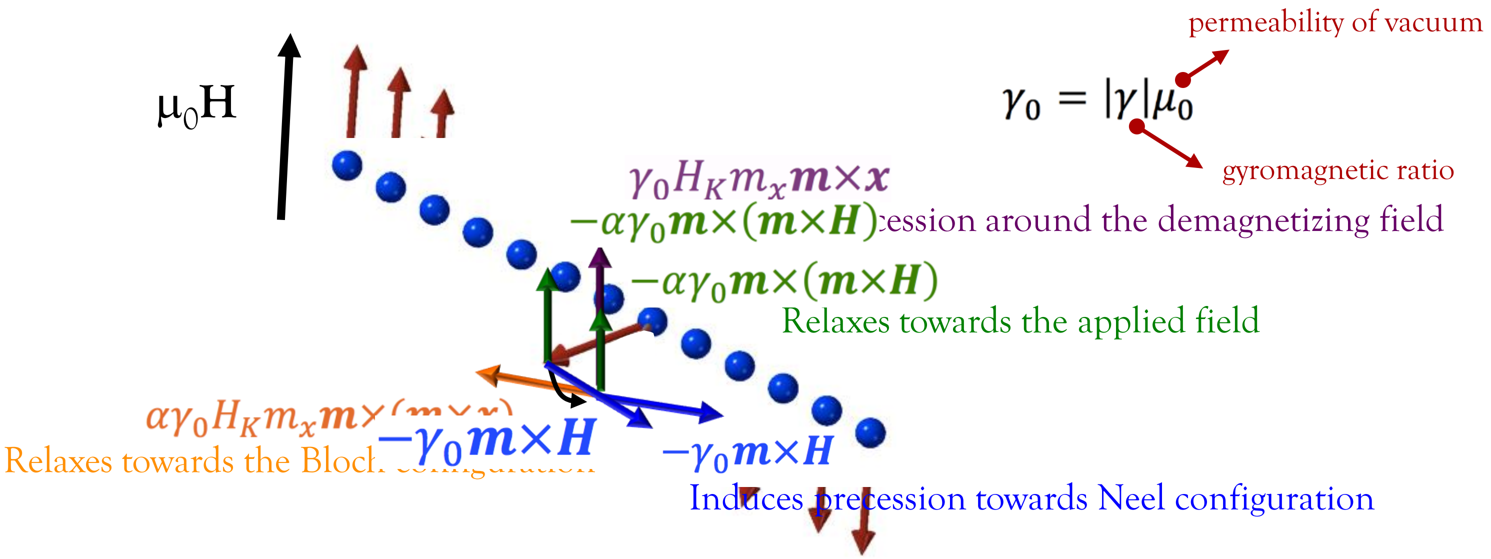
ier EPL 2004...



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

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

Domain wall profile

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

Exchange Perpendicular aniso

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

chirality velocity width

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

$$\varphi = \varphi(t), \Delta = \sqrt{A/K_\perp}$$

How does the torque look like?

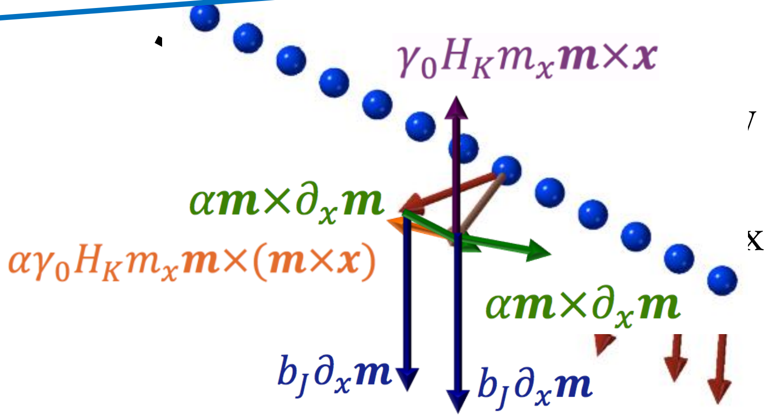
$$\boldsymbol{T} = \tau_{||}\boldsymbol{m}\times(\boldsymbol{p}\times\boldsymbol{m})$$

What does it do?

Berger's field

$$b_J = \frac{P\mu_B}{eM_s}J_c \quad \Delta\partial_t\varphi = s\frac{\gamma_0\Delta H_K}{2}\sin \quad H_{ex} = \frac{1}{\delta}\frac{P\hbar}{eM_s}J_c\,\boldsymbol{m}$$

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



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

$$\sin 2\varphi = -\frac{2sb_J}{\gamma_0 H_K\Delta} \qquad v = b_J$$

$$v = 0$$

One-dimensional model

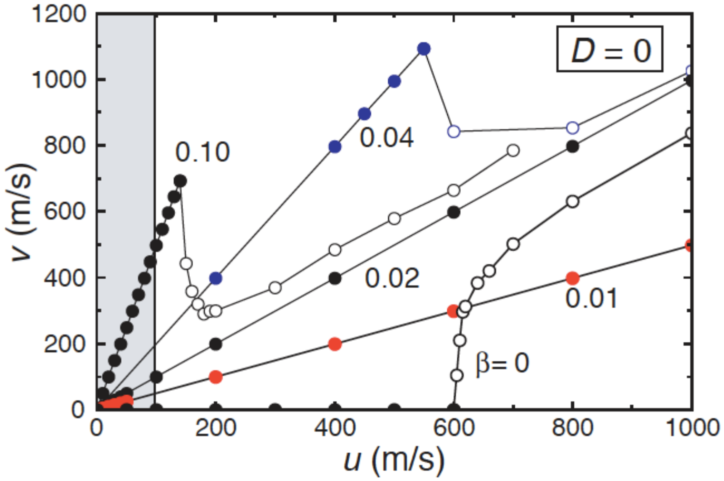
How to break the compensation between the adiabatic torque and the dipolar energy?

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

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

$$\partial_t\varphi \neq 0$$

$$v = b_J$$

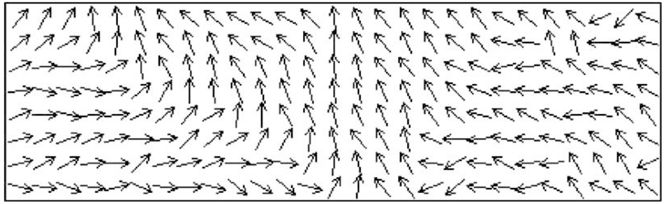
Driven by the adiabatic torque

Experimental observations

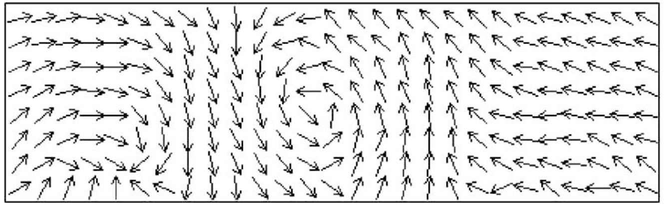
Domain wall motion in permalloy

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

Transverse wall

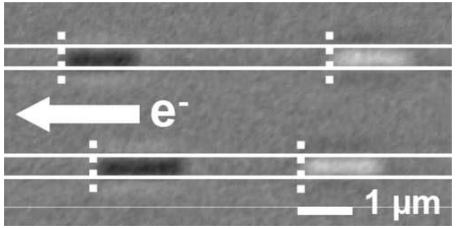


Vortex wall

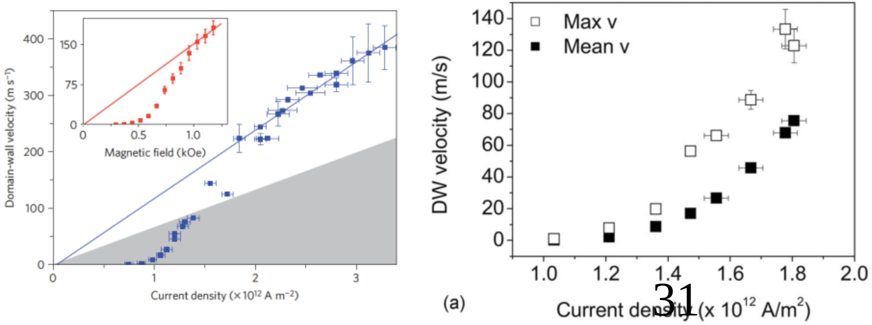


Klaui, Physical Review Letters 95, 026601 (2005)

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)

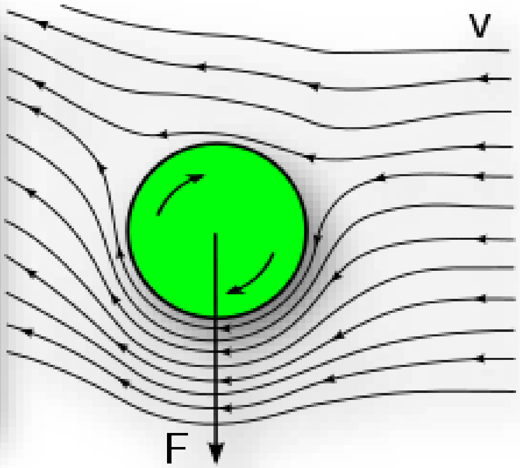
Spin-orbitronics

A tale of spinning balls

A tale of spinning balls

A tale of spinning balls

Heinrich Magnus
1802-1870



J.W.M. Bush, The aerodynamics of the beautiful game, 2013.
In *Sports Physics*, Ed. C. Clanet, Les Editions de l'Ecole Polytechnique, p.171-192.

Spin-orbit in a nutshell

Electron's momentum

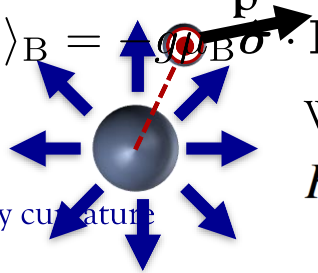
$$\hat{\mathcal{H}}_{\mathrm{so}} = -\frac{e\hbar}{2m^2c^2}\hat{\boldsymbol{\sigma}}\cdot(\boldsymbol{\nabla}V\times\hat{\mathbf{p}})$$

Spin Potential gradient

In atoms, $\boldsymbol{\nabla}V \approx \frac{\partial_r V}{r}\mathbf{r}$ $\Rightarrow$ $\hat{\mathcal{H}}_{\mathrm{so}} = \xi_{\mathrm{so}}\hat{\boldsymbol{\sigma}}\cdot\hat{\mathbf{L}}$

In crystals, the spin-orbit coupling induces a *momentum-dependent effective field*

$$\langle\hat{\mathcal{H}}_{\mathrm{so}}\rangle_{\mathrm{B}} = -g\mu_{\mathrm{B}}\hat{\boldsymbol{\sigma}}\cdot\hat{\mathbf{B}}_{\mathbf{k}}$$



With inversion symmetry

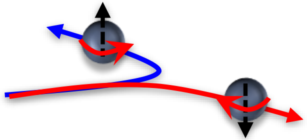
$$\hat{\mathbf{v}}_s = \partial_{\hbar\mathbf{k}}\hat{\mathbf{B}}^s_{\mathbf{k}} + \hat{\mathbf{B}}^s_{\mathbf{k}}\boldsymbol{\Omega}_{\mathbf{k}}\times\dot{\mathbf{k}}$$

Berry curvature

Without inversion symmetry

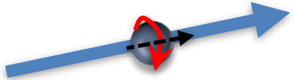
$$H_{\mathrm{R}} \approx -\alpha\hat{\boldsymbol{\sigma}}\cdot(\mathbf{z}\times\mathbf{k})$$

Spin Hall e



D'yakonov, Perel Phys. Lett. 35A, 459 (1971)

pin galvanic effect

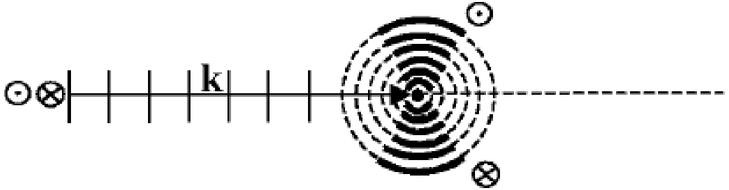


Ivchenko JETP Lett. 27, 604 (1978)

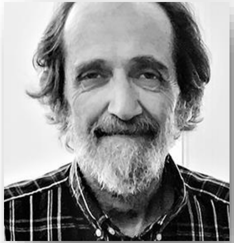
Spin Hall effect

Michel D'yakonov

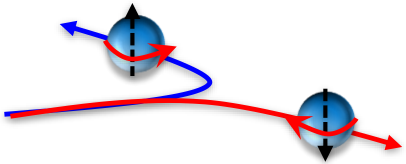
Vladimir Perel'



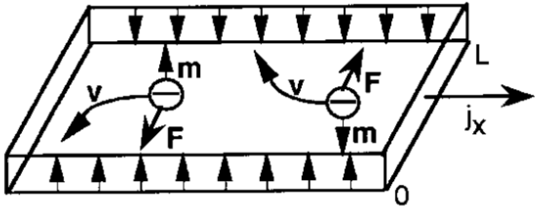
Because of Mott spin-dependent scattering,
a pure spin current can be generated,
transverse to the injected current

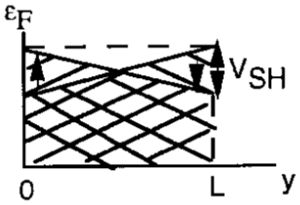


Jorge Hirsch



D'yakonov, Perel Phys. Lett. 35A, 459 (1971)
Hirsch, Physical Review Letters 83, 1834 (1999)





Three main mechanisms for spin (and anomalous) Hall effects

Berry curvature

Robert Karplus

Joaquin Luttinger

The wave function's Berry curvature induces an *anomalous velocity*

$$\boldsymbol{v}_n = \frac{1}{\hbar}\frac{\partial \varepsilon_n}{\partial \boldsymbol{k}} + \frac{e}{\hbar}\boldsymbol{E}\times\boldsymbol{\Omega}_n$$

$$\sigma_{xy} = -\frac{\hbar e^2}{\Omega}\sum_{n\neq m}\frac{2\mathrm{Im}\langle n|\hat{v}_x|m\rangle_0\langle m|\hat{v}_y|n\rangle_0}{(\varepsilon_n-\varepsilon_m)^2} f_n$$

The Hall current is *intrinsic* and associated with *interband transitions*

$$\sigma_{xy} \sim \mathrm{Const.}$$

$$\rho_{xy} \approx \frac{\sigma_{xy}}{\sigma_{xx}^2} \sim \rho_{xx}^2$$

Karplus, Luttinger, Physical Review 95, 1154 (1954)

Side jump

Luc Berger

Scattering against spin-orbit coupled impurities induces an *anomalous velocity*

$$\hat{\boldsymbol{v}} = \frac{1}{\hbar}\partial_{\boldsymbol{k}}\widehat{\mathcal{H}}_0 + \xi_{so}\hat{\boldsymbol{\sigma}}\times\boldsymbol{\nabla}V_{imp}(\boldsymbol{r})$$

The Hall effect is *extrinsic,* the Hall angle is *proportional* to the scattering rate

$$\theta_{SJ} = \beta\frac{m^*\xi_{so}}{\hbar^2\tau_0}$$

$$\sigma_{xy} \sim \mathrm{Const.}$$

$$\rho_{xy} \approx \frac{\sigma_{xy}}{\sigma_{xx}^2} \sim \rho_{xx}^2$$

Berger, Physical Review B 2, □4559 (1970)

Skew scattering

Nevill Mott

The scattering probability on spin-orbit coupled impurities is also *spin-dependent*

$$P^{\sigma\sigma(2)}_{\boldsymbol{k}'\boldsymbol{k}} \sim n_i V_0^3 \mathcal{N}_F \xi_{so}\boldsymbol{\sigma}_{\sigma\sigma}\cdot(\boldsymbol{k}'\times\boldsymbol{k})$$

The Hall effect is *extrinsic* but the Hall angle is *independent* of scattering time

$$\theta_{SS} = \beta\frac{2\pi}{3}\frac{k_F^2\xi_{so}}{\hbar}N_F V_{imp}$$

$$\sigma_{xy} \sim \sigma_{xx}$$

$$\rho_{xy} \sim \frac{\sigma_{xy}}{\sigma_{xx}^2} \rho_{xx}$$

Smit, Physica Review 24, 39 (1958)

Spin Hall effect

Experimental detection of spin Hall effect

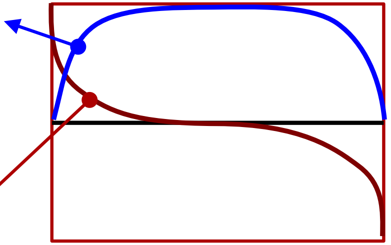
Diffusive theory of spin Hall accumulation

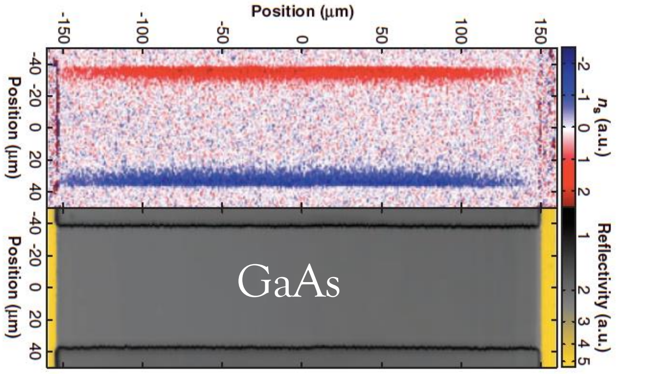
$$\boldsymbol{J}_s = \ J_s = -\sigma_0 \partial_z \mu_s - \theta_H J_c \otimes \boldsymbol{\sigma}$$

$$\partial_z^2 \mu_s = -\frac{\mu_s}{\lambda_{sf}}$$

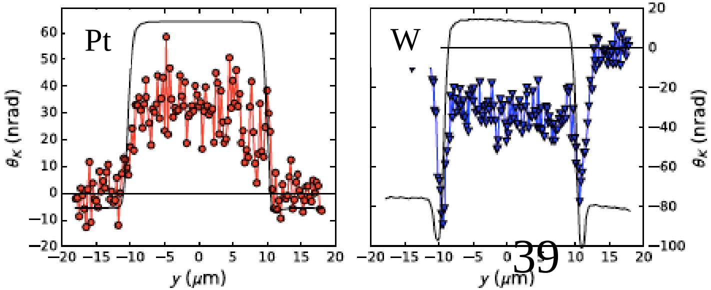
$$J_s = \sigma_0 \theta_H \left(\frac{\cosh \frac{z}{\lambda_{sf}}}{\cosh \frac{d}{\lambda_{sf}}} - 1 \right)$$

$$\mu_s = -\lambda_{sf} \theta_H \frac{\sinh \frac{z}{\lambda_{sf}}}{\cosh \frac{d}{\lambda_{sf}}}$$





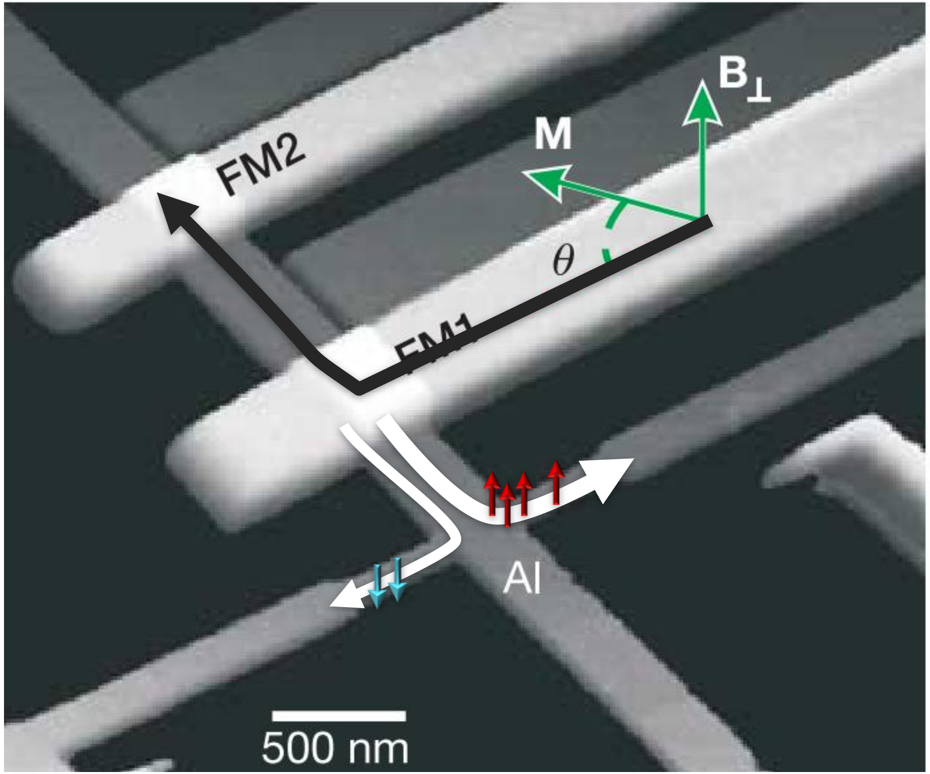
Kato et al., Science 306, 1910 (2004)

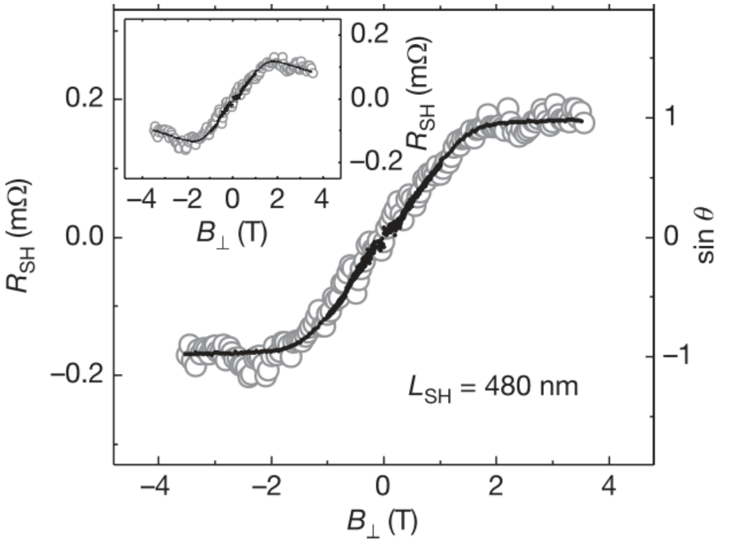


Stamm, Physical Review Letters 119, 087203 (2017)

Spin Hall effect

Nonlocal detection



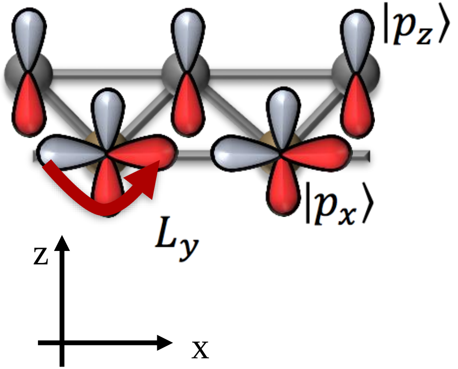


Valenzuela and Tinkham, Nature 442, 176 (2006)
Kimura et al., PRL **98**, 156601 (2007)

Rashba-Edelstein effect

A toy model for interfacial spin-momentum locking

Consider an atomic chain with p-orbitals



Top p_z — p_z-p_z hopping — p_z-p_x hopping

$$H = \begin{pmatrix} \boxed{\varepsilon_k^T} & \boxed{V_{zz}} & \boxed{V_{zx}} \\ V_{zz}^* & \boxed{\varepsilon_k^0} & 0 \\ V_{zx}^* & 0 & \boxed{\varepsilon_k^0} \end{pmatrix}$$

Bottom p_z — Bottom p_x

Slater-Koster parametrization

$$V_{zz} = (V_\sigma + V_\pi)\cos k_x a$$
$$V_{zx} = -i(V_\sigma - V_\pi)\sin k_x a$$

The diagonalization brings three eigenstates. For instance

$$\varepsilon_0(k) = \varepsilon_k^0, |0\rangle = \frac{1}{\sqrt{|V_{zz}|^2 + |V_{zx}|^2}}(-V_{zx}|p_z\rangle + V_{zz}|p_x\rangle)$$

The orbital moment of this state reads

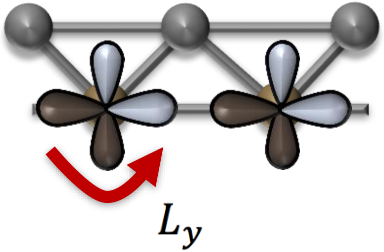
$$\langle 0|\boldsymbol{L}|0\rangle = \frac{}{(V_\sigma + V_\pi}\langle 0|\boldsymbol{L}|0\rangle = \frac{2V_{zx}V_{zz}}{|V_{zz}|^2 + |V_{zx}|^2}\boldsymbol{y}\frac{\sin 2k_x a}{k_x a}\boldsymbol{y}$$

Symmetry breaking promotes orbital mixing, and non-vanishing orbital moment

See G. Manchon et al., Physical Review B **101**, 174423 (2020)

Rashba-Edelstein effect

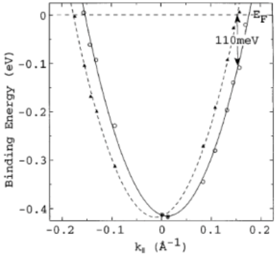
E. Rashba



Orbital Rashba effect $L_y \sim k_x$

Spin-orbit coupling $\xi_{so}\boldsymbol{L}\cdot\boldsymbol{S}$

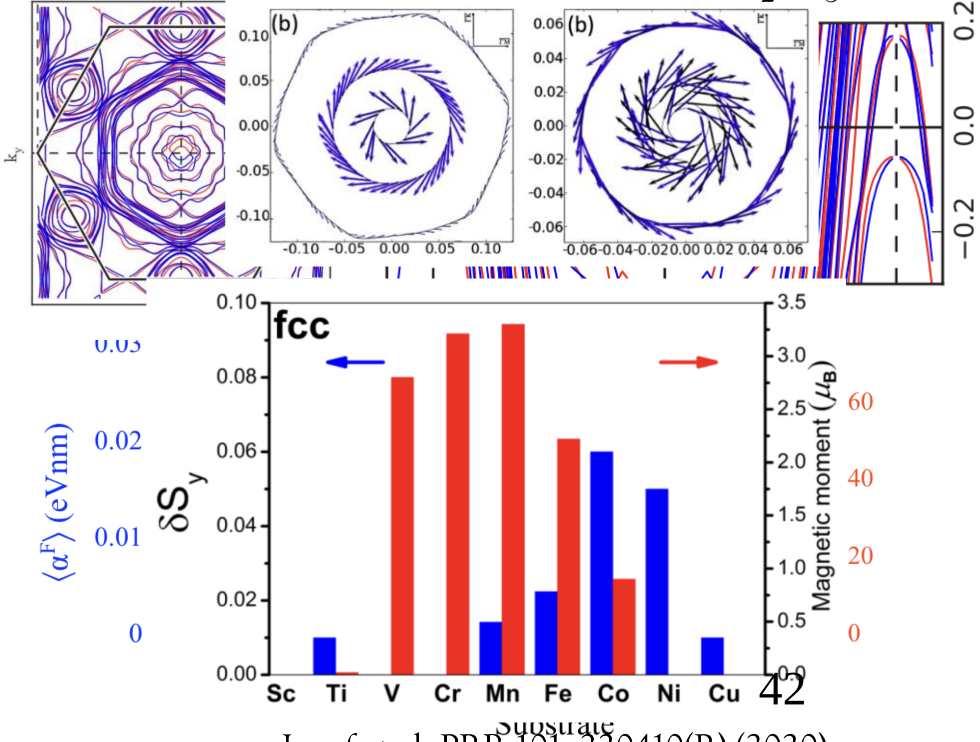
Tadaaa.... $H_R = -\alpha_R \boldsymbol{\sigma}\cdot(\boldsymbol{z}\times\boldsymbol{k})$



Lashell et al., PRL 77. 3419 (1996)

Transition metal interfaces: (4d;5d)/Co

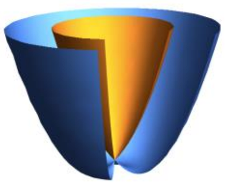
Topological insulator interfaces: Bi_2Se_3/3d

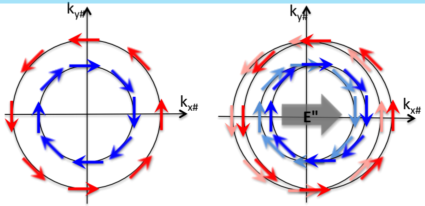


Laref et al. PRB 101, 220410(R) (2020)

Grytsyuk et al. PRB 93, 174421 (2016)

Rashba-Edelstein effect

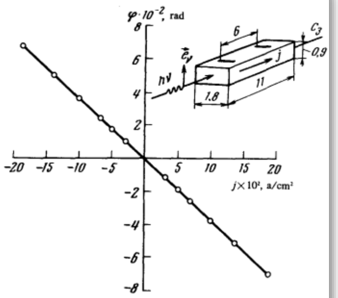




$$\vec{S} \propto \vec{y} \Rightarrow \vec{T} = D\vec{m} \times \vec{S} \propto \vec{y} \times \vec{m}$$

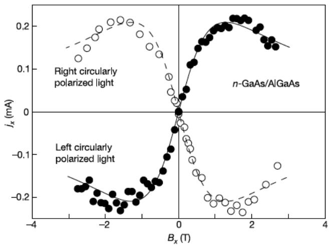
Ivchenko & Pikus, Pis'ma Zh. Eksp. Teor. Fiz 27, 604 (1978)
Edelstein, Solid State Com. 73, 233 (1990)

Tellurium



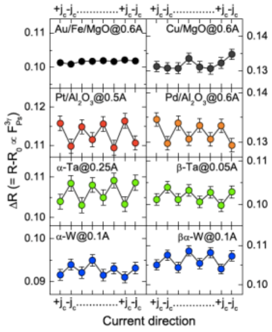
Vorob'ev, JETP Lett. 29, 441 (1979)

GaAs-QW



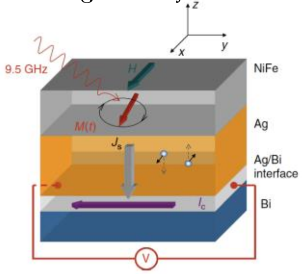
Ganichev, Nature 417, 153 (2002)

TM-surfaces



Zhang, Sci. Rep. 4:4844 (2014)

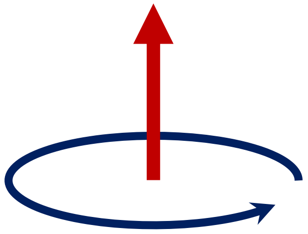
Ag/Bi surfaces



Rojas-Sanchez, Nature Comm. 4:2944 (2013)

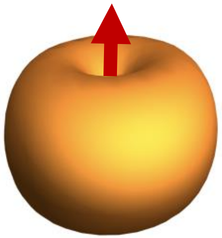
Manchon et al., Nature Materials 14, 871 (2015)
Bihlmayer et al., Nature Physics Reviews (2022)

Orbitronics: the new frontier?

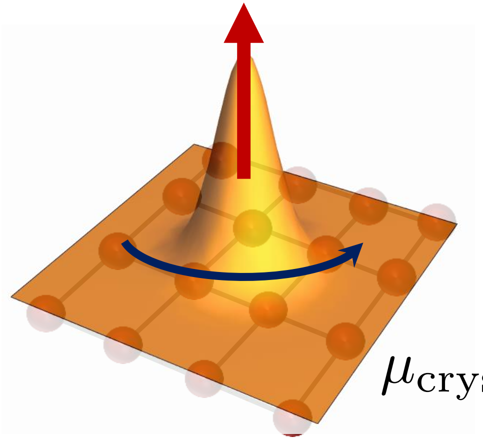


$\mu = IA$

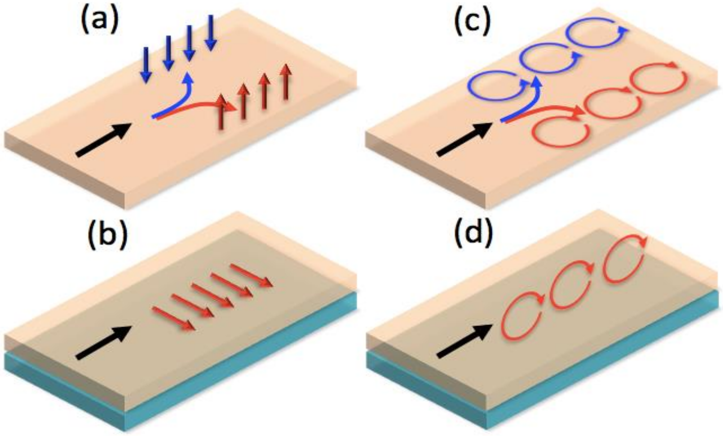
$\mu_s = \frac{g_s e}{2m}\frac{\hbar}{2}$

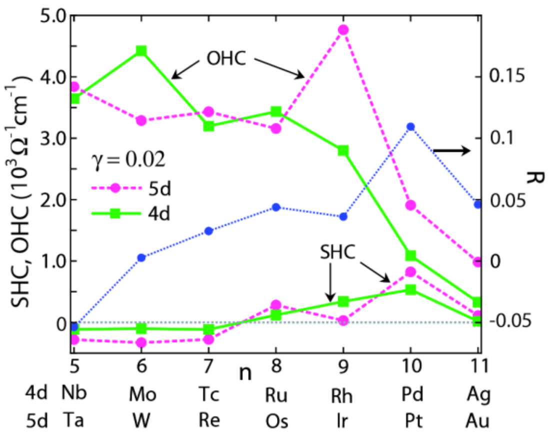


$\mu_l = \frac{g_l e}{2m}\hbar$



$\mu_{\text{crystal}} = ?$

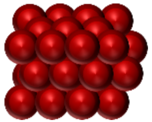




Kontani PRL 2009
Tanaka PRB 2008
Jo PRB 2018
Salemi PRM 2022

Orbitronics: the new frontier?

Orbital Rashba effect in W and V (d orbitals only) – Slater-Koster parameterization



The tight-binding model in a nutshell

$$\mathcal{H}_0 = \mathcal{H}_{\rm mono} \otimes \hat{\sigma}_0 + \mathcal{H}_{\rm ex} + \mathcal{H}_{\rm soc}.$$

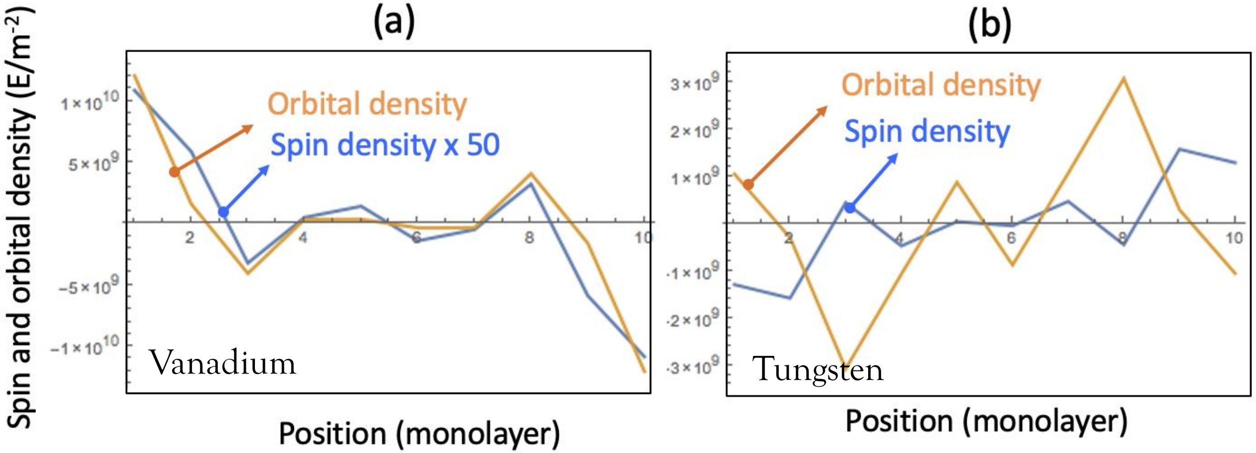
1d hexagonal lattice Slater-Koster
$d_{xy}, d_{yz}, d_{zx}, d_{z^2}, d_{x^2-y^2}$

"s-d" magnetic exchange

Russel-Saunders spin-orbit coupling

$$\mathcal{H}_{\rm layer} = \begin{pmatrix} \mathcal{H}_0 & \mathcal{T}_1 & \mathcal{T}_2 & 0 & \\ \mathcal{T}_1^\dagger & \mathcal{H}_0 & \mathcal{T}_1 & \mathcal{T}_2 & \ddots \\ \mathcal{T}_2^\dagger & \mathcal{T}_1^\dagger & \mathcal{H}_0 & \mathcal{T}_1 & \ddots \\ 0 & \mathcal{T}_2^\dagger & \mathcal{T}_1^\dagger & \mathcal{H}_0 & \ddots \\ & \ddots & \ddots & \ddots & \ddots \end{pmatrix}$$

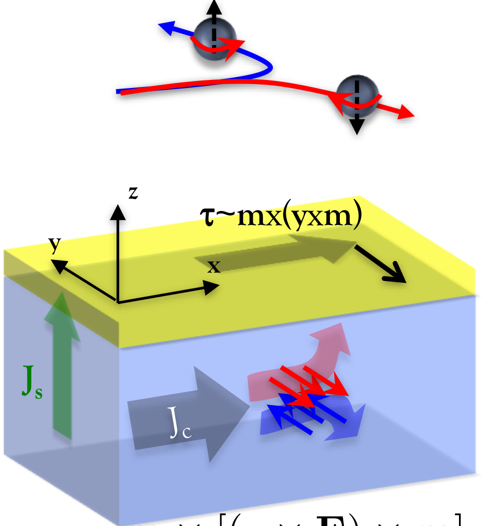
See G. Manchon et al., Physical Review B **101**, 174423 (2020)



Spin-orbit physics at interfaces

Spin Hall effect

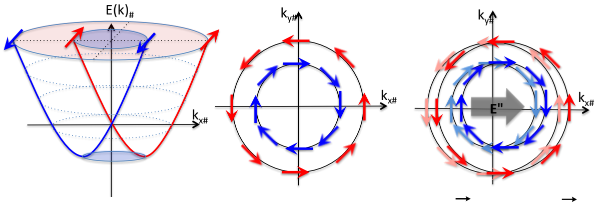
$$\hat{\mathbf{v}}_s = \partial_{\hbar\mathbf{k}}\varepsilon^s_{\mathbf{k}} + s\hat{\mathbf{\Omega}}_{\mathbf{k}} \times \dot{\mathbf{k}}$$



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

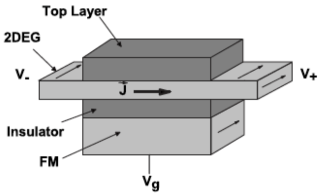
See Haney et al., PRB 87, 174411 (2013)

Inverse spin galvanic (Rashba) effect



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

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

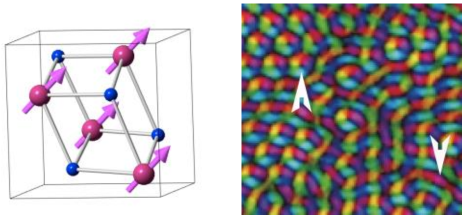


$$\boldsymbol{\tau} = \tau_{\perp}\mathbf{m} \times (\mathbf{z} \times \mathbf{E})$$

Manchon & Zhang, PRB 78, 212405 (2008)

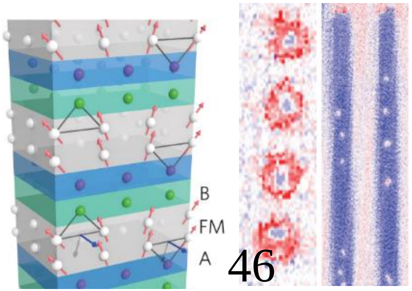
Dzyaloshinskii-Moriya Interaction

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



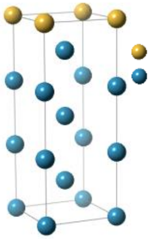
Yu, Nature 465, 901 (2010)

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

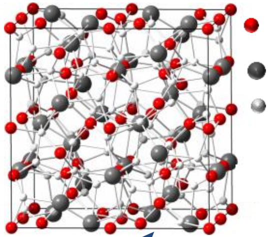


Moreau-Luchaire, Nat. Nano 11, 444 (2016)

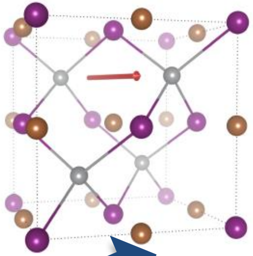
Magnetic metal heterostructures



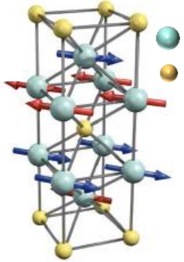
Magnetic Insulators
YIG, TmIG...



Non-centrosymmetric magnets
(Ga,Mn)As, MnNiSb



Antiferromagnets
Mn_2Au, CuMnAs, NiO

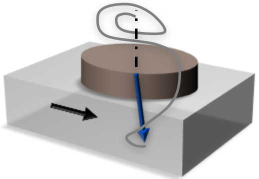


Spin-Orbit Torques

$$\hat{H}_{\rm so} = (\xi/\hbar)\hat{\boldsymbol{\sigma}} \cdot (\boldsymbol{\nabla} V \times \hat{\mathbf{p}})$$

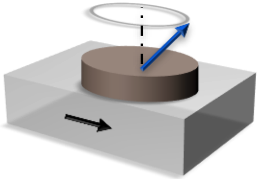
Manchon et al.,
RMP 91, 035004 (2019)

Magnetization switching



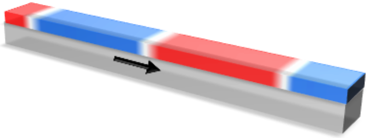
Magnetic Memories

High-frequency oscillations



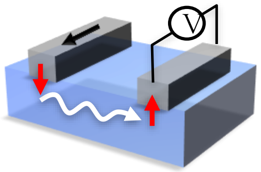
Nano-oscillators

Domain wall & skyrmion motion



Race-track memories

Spin-wave Excitations

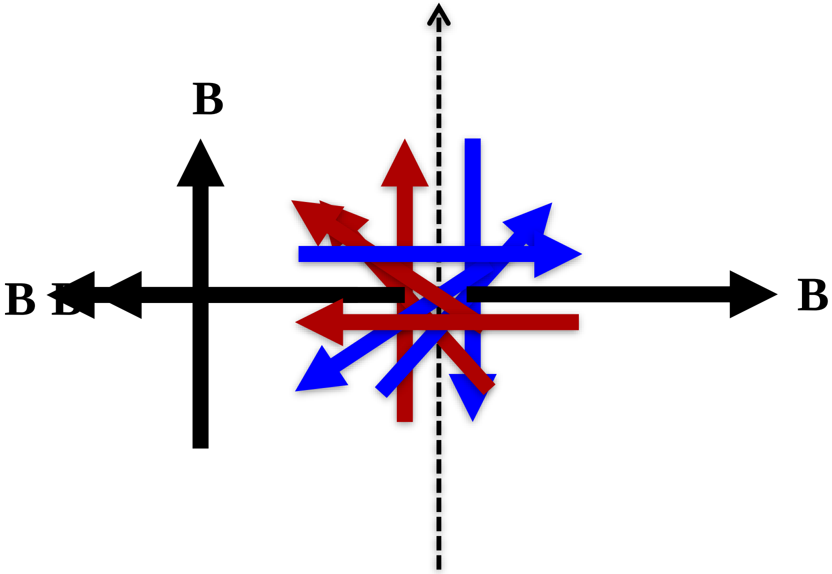


Interconnects & spin logic

Three interesting consequences

a. Electrical control of antiferromagnets
b. Chiral walls and skyrmions
c. Topological insulators

Spin-orbit torque in antiferromagnets

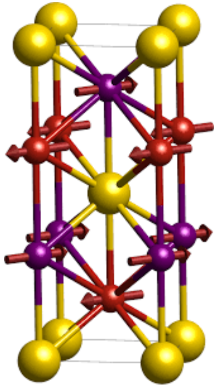


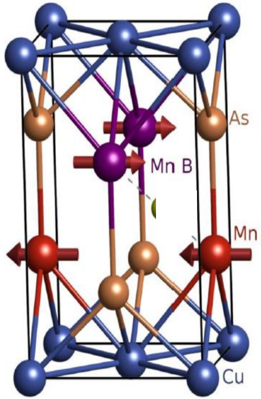
Baltz, Manchon et al., Review of Modern Physics **90**, 015005 (2018)

Spin-orbit torque in antiferromagnets

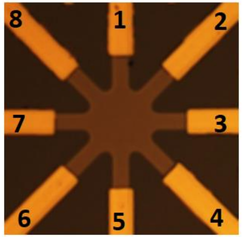
Staggered field on inversion partners

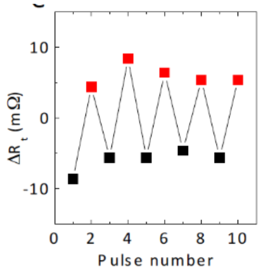
Mn_2Au CuMnAs





Zelezny et al., PRL 113, 157201 (2014)

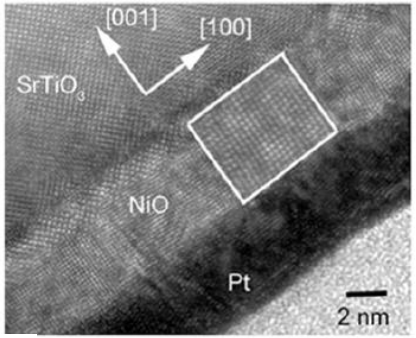


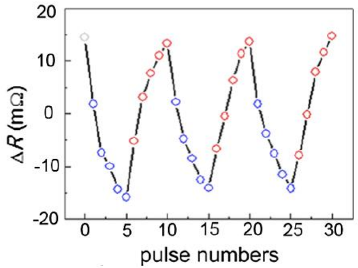


Wadley et al., Science 351, 587 (2016)

Damping-like torque

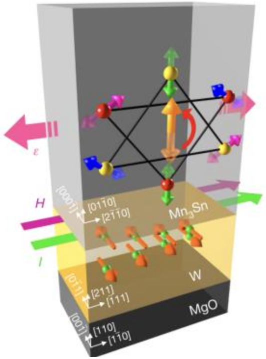
Layered Collinear NiO

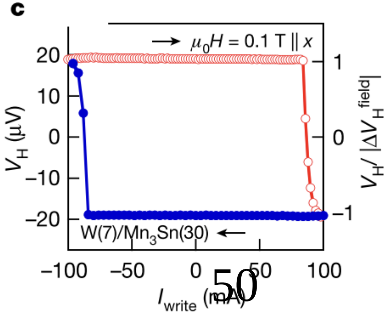




Chen, PRL 120, 207204 (2018)
Baldrati, PRL 123, 177201 (2019)

Noncollinear Mn_3Sn



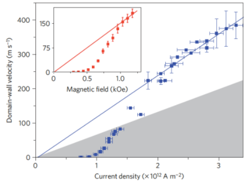


Higo, Nature 607, 474 (2022)

Three interesting consequences

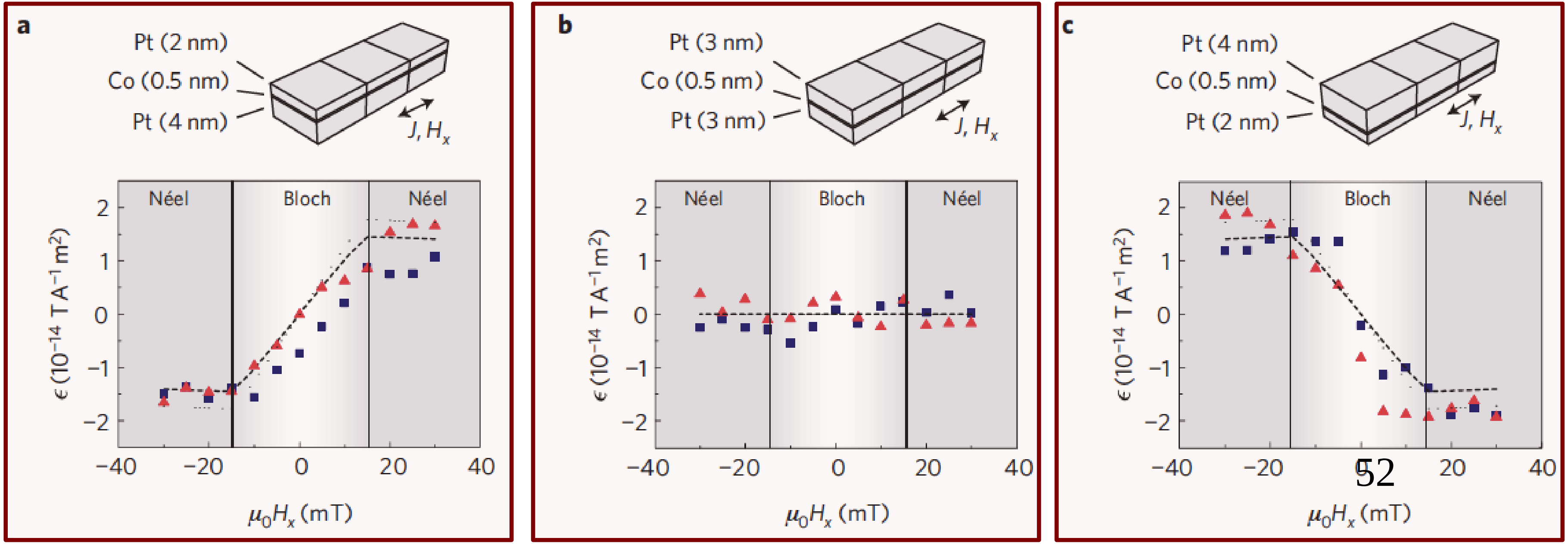
a. Electrical control of antiferromagnets
b. Chiral walls and skyrmions
c. Topological insulators

Chiral domain walls



Miron, Nature Materials 10, 419 (2011)

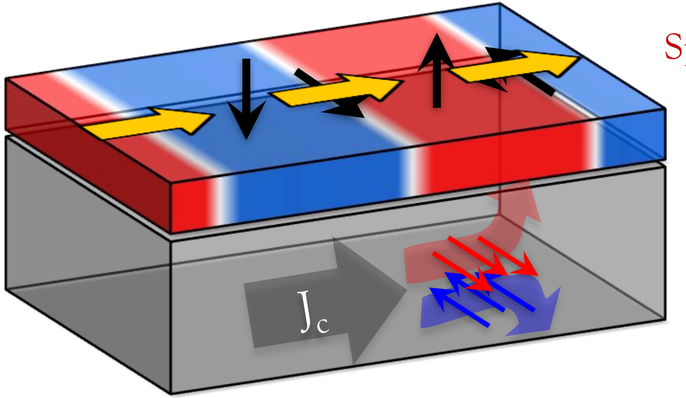
The domain wall flows along the electron direction
The domain wall velocity is much larger than usual
Inversion symmetry breaking seem to play a central role



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

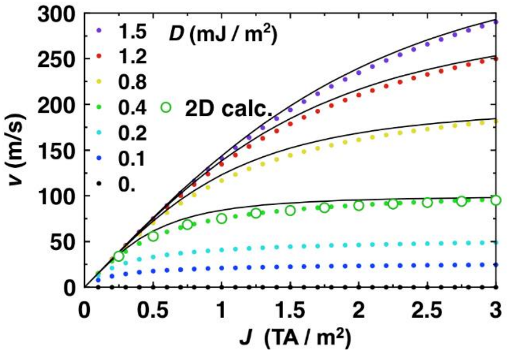
Spin Hall torque

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

Spin Hall efficiency

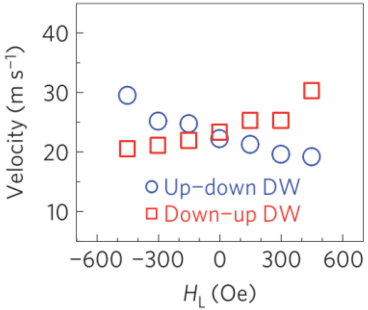
Current density

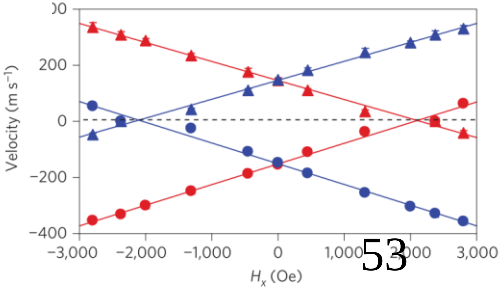
$$v = \frac{\gamma_0 \Delta H_D}{\sqrt{1 + (J_D/J)^2}} \qquad J_D = \frac{2\alpha t e D}{\hbar\theta_H \Delta}$$



Thiaville, EPL 100, 57002 (2012)

Experiments confirm the presence of an internal field

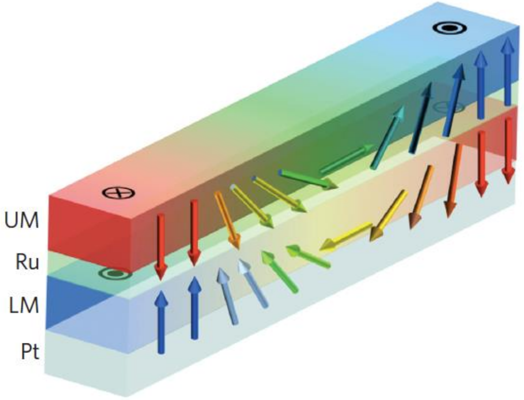


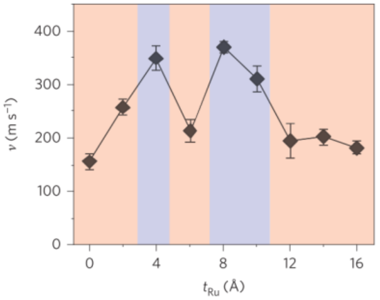


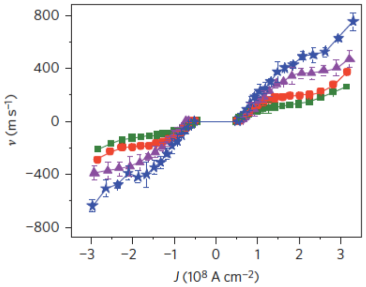
Emori, Nature Materials 12, 611 (2013)
Ryu, Nature Nanotechnology 8, 527 (2013)

Chiral domain walls

Synthetic antiferromagnets







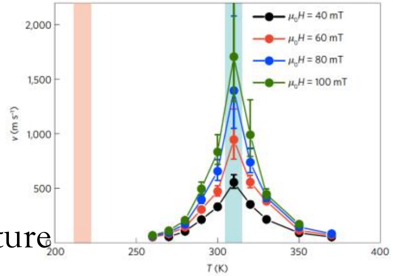
Yang, Nature Physics 10, 221 (2015)

Compensated ferrimagnets

Field-driven

GdFeCo

Maximum velocity at angular momentum compensation temperature

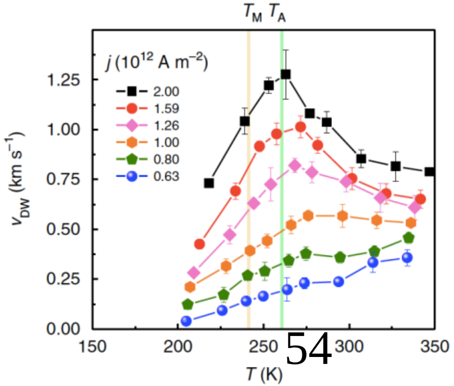


Kim, Nature Physics 16, 1187 (2017)

Current-driven

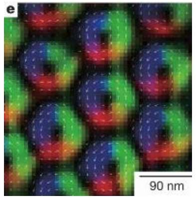
$Pt/Gd_{44}Co_{56}$

Same physics induces velocities up to 1.3km/s !



Caretta, Nature Nanotechnology 13, 1154 (2018)

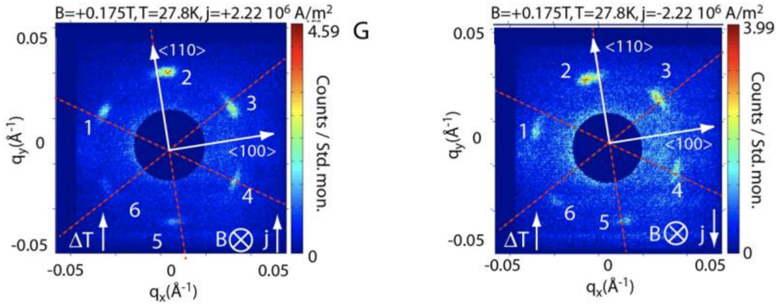
Skyrmion dynamics



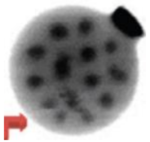
MnSi, T<30 K

First observation of
stable skyrmion lattices
in bulk MnSi magnet

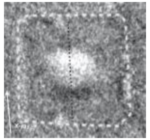
Yu Nature 465, 901 (2010)
Mühlbauer Science 323, 915 (2009)



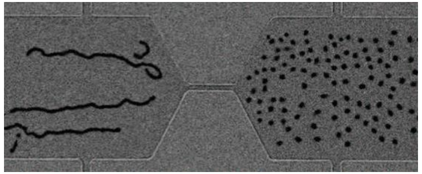
Jonietz Science 330, 1648 (2010)
Schultz Nature Physics 8, 301 (2012)



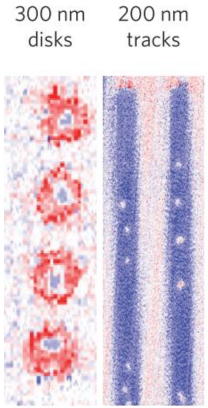
Pt/Co/Ta



Pt/Co/MgO

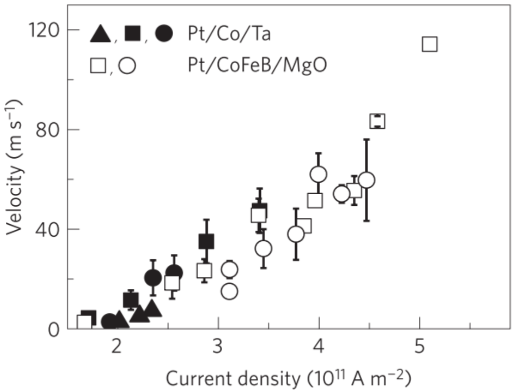


Ta/CoFeB/TaOx

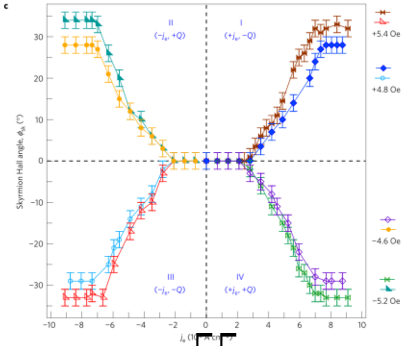


$(Ir/Co/Pt)_{10}$

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)

Three interesting consequences

a. Electrical control of antiferromagnets
b. Chiral walls and skyrmions
c. Topological insulators

Layman's vision of topological insulators

Quantum Hall effect

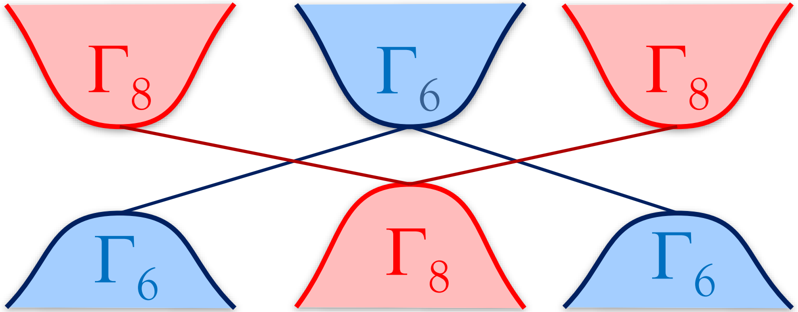
$\omega_B \sim B \gg 1/\tau$

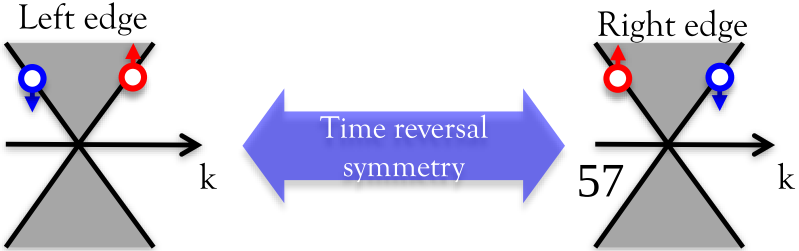
spin Hall effect

$B_{so} \gg 1/\tau$

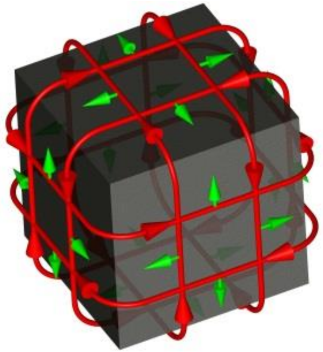
Qi and Zhang, Rev. Mod. Phys. 83, 1057 (2010)
Hasan and Moore Annu. Rev. Condens. Matter Phys. 2, 55 (2010)

S.C. Zhang B.A. Bernevig T. Hugues



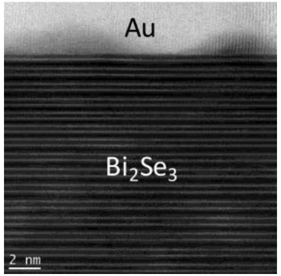


Three dimensional topological insulators

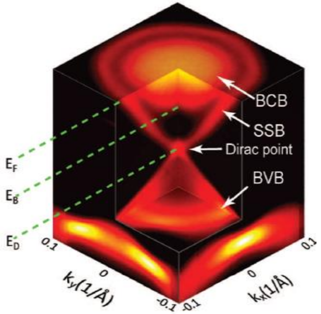


http://www.physics.umd.edu/DrewGroup

Bi_2Te_3, Bi_2Se_3, α-Sn etc.



J. Phys. Chem. C 121, 23551 (2017)

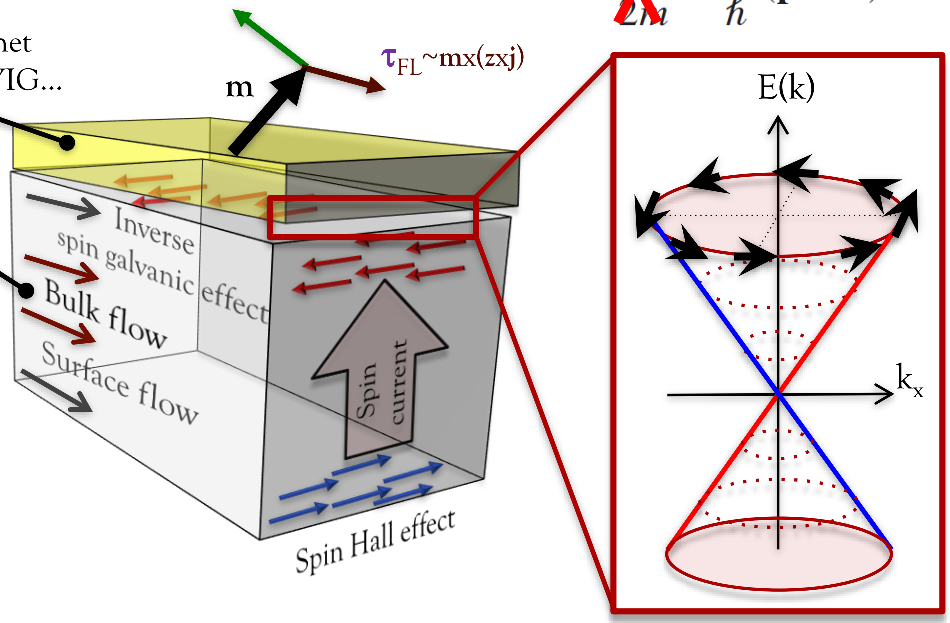


Chen, Science 2010

Ferromagnet
Co, Fe, Ni, YIG...

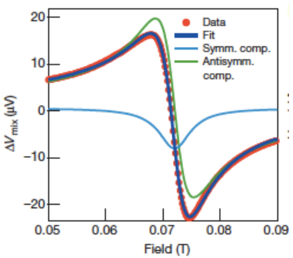
Bi_2Se_3,
$(Bi,Sb)_2Te_3$

$$H = \cancel{\frac{p^2}{2m}} + \frac{\alpha_R}{\hbar}(\mathbf{p}\times\hat{\mathbf{z}})\cdot\boldsymbol{\sigma}$$



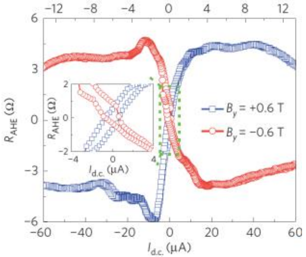
Large spin-orbit torque at room temperature

Bi_2Se_3/NiFe



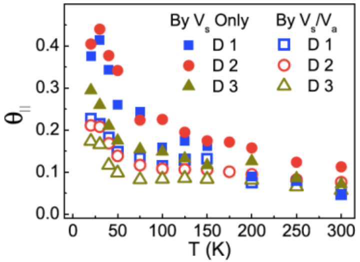
Mellnik, Nature 511, 449 (2014)

$(Bi,Sb)_2Te_3/(Cr,Bi,Sb)_2Te_3$



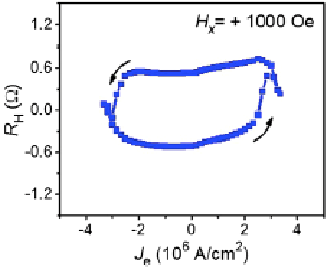
Fan, NatMat 13, 699 (2014)

Bi_2Se_3/CoFeB



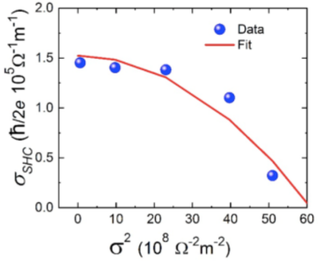
Wang, PRL 114, 257202 (2015)

Bi_2Se_3/CoTb

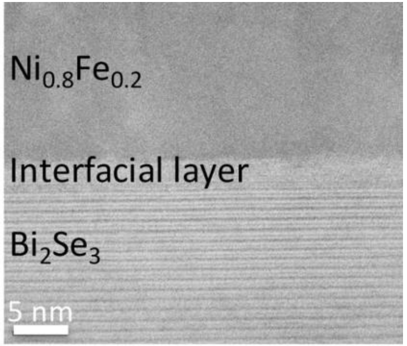


Han, PRL 119, 077702 (2017)

Bi_xSe_{1-x}/CoFeB



Mahendra, NatMat 17, 800 (2018)

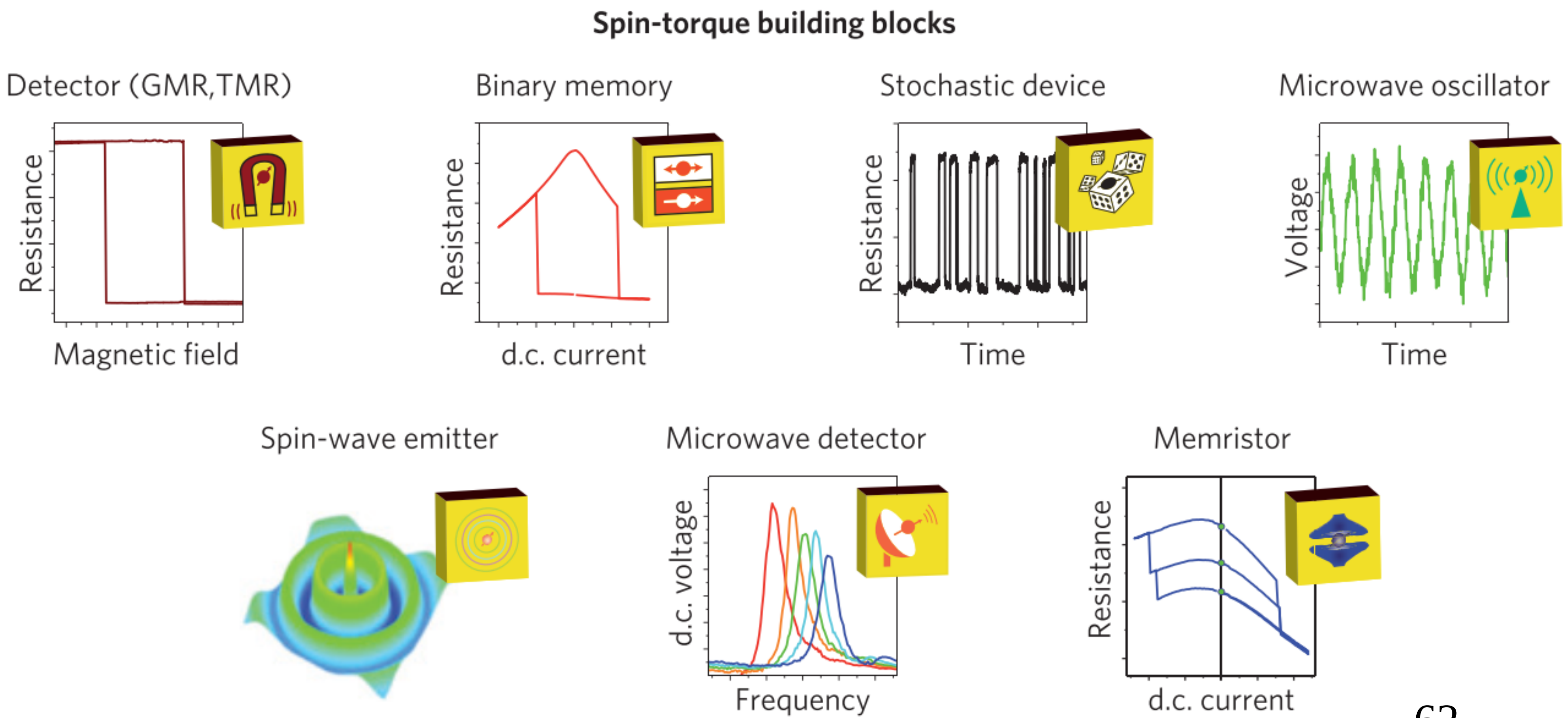


Parameters	$Bi_xSe_{(1-x)}$ (This work)	Bi_2Se_3 Mellnik	β -W	Pt
σ ($\Omega^{-1}m^{-1}$)	0.78×10^4	5.7×10^4	4.7×10^5	4.2×10^6
σ_{SH} ($\frac{\hbar}{2e}$ $\Omega^{-1}m^{-1}$)	1.5×10^5	2.0×10^5	1.9×10^5	3.4×10^5
θ_{SH}	18.83	3.5	0.4	0.08
J_{sw} (A/cm^2)	4.3×10^5	--	1.6×10^6	2.85×10^7-10^8


That's all folks!
Hope you liked it!

BONUS!!
Spin torque devices

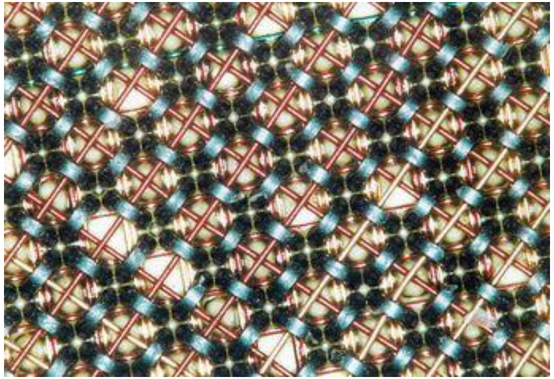
The many opportunities of spin transfer torque

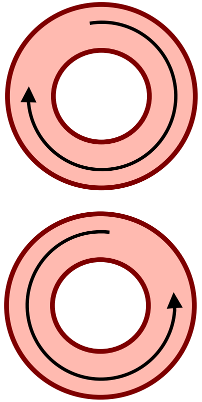


Locatelli et al., Nature Materials 13, 11 (2013)

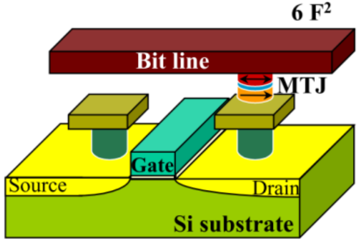
Magnetic random-access memories

IBM magnetic core memories

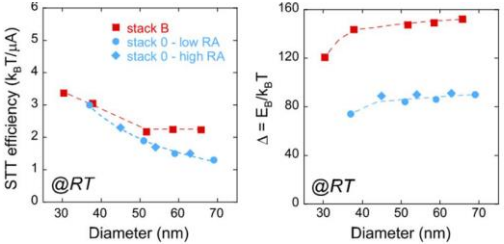




Spin torque-driven MRAM

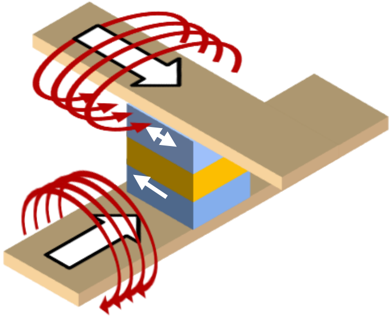


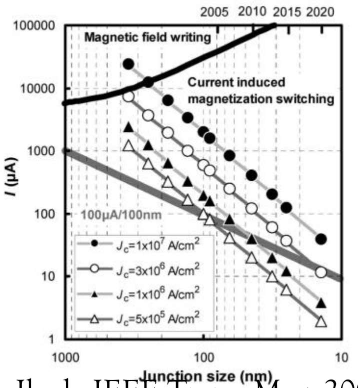
Apalkov Proc. IEEE 104, 1796 (2016)



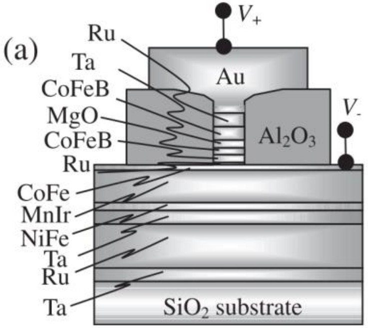
Thomas JAP 115, 172615. (2014)

Field-driven MRAM





Ikeda IEEE Trans. Mag. 2007



Hayakawa JJAP 44, L587 (2005)

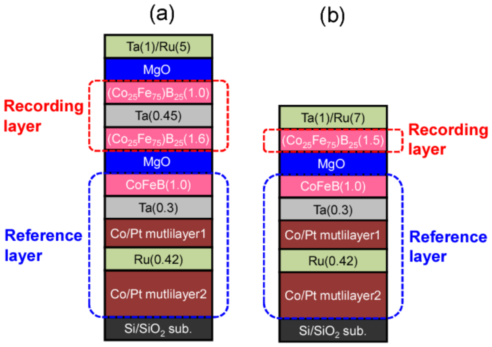


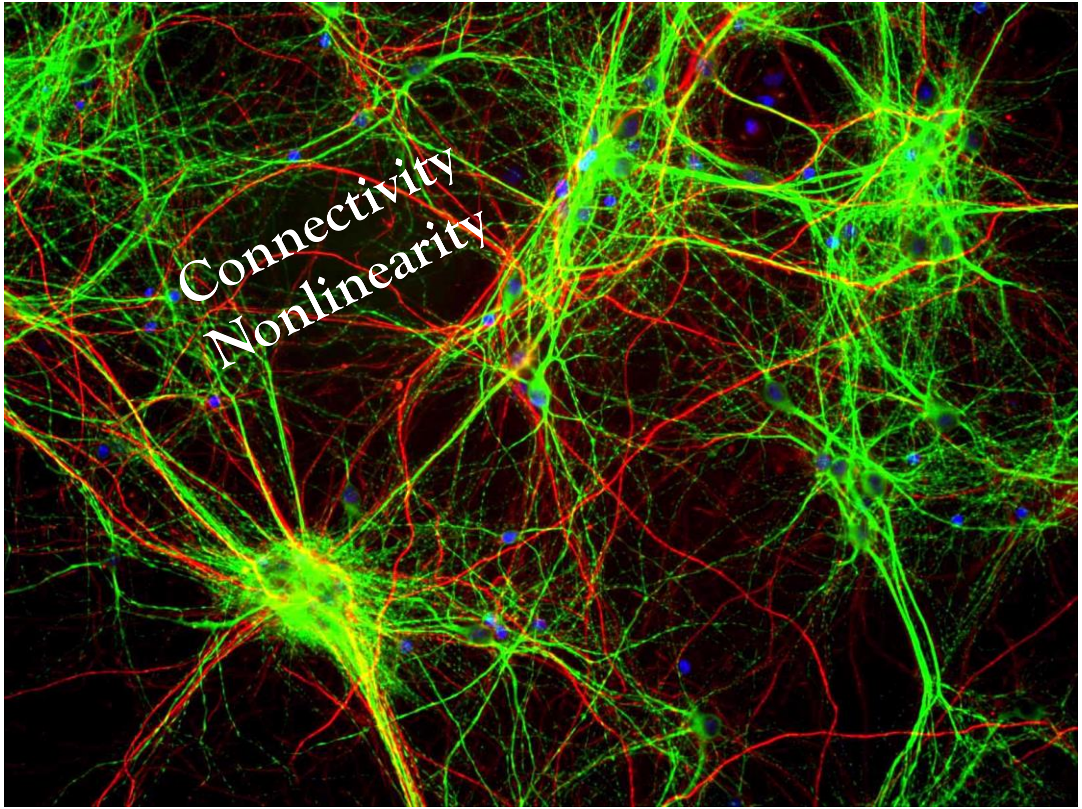
Fig. 1 Stack structures of magnetic tunnel junctions with perpendicular

Ikeda IEDM 2014

Naganuma VLSI 2021

Thermal stability and critical switching current

Nano-oscillators and neuromorphic computing



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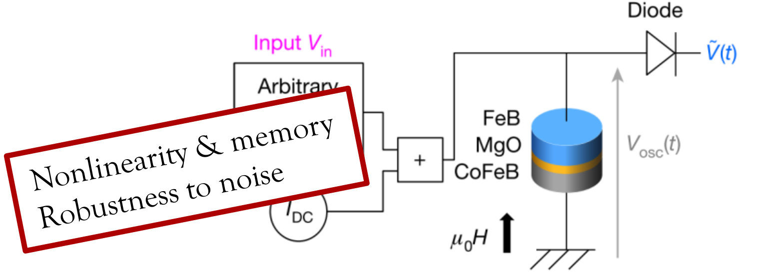
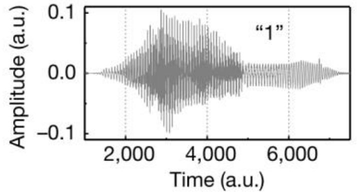
Nano-oscillators and neuromorphic computing

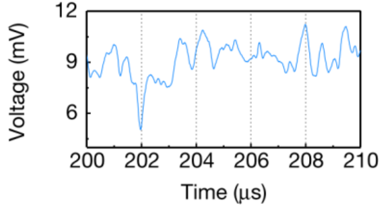
A single nanooscillator as a reservoir emulator

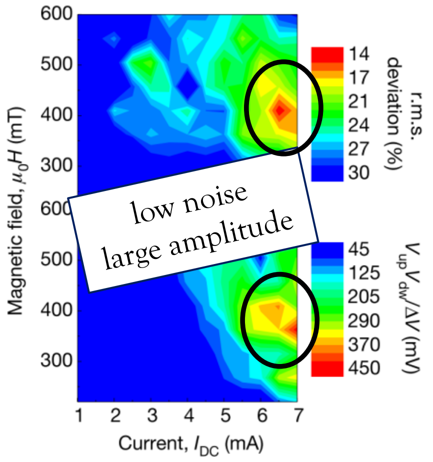


Neural network in time domain



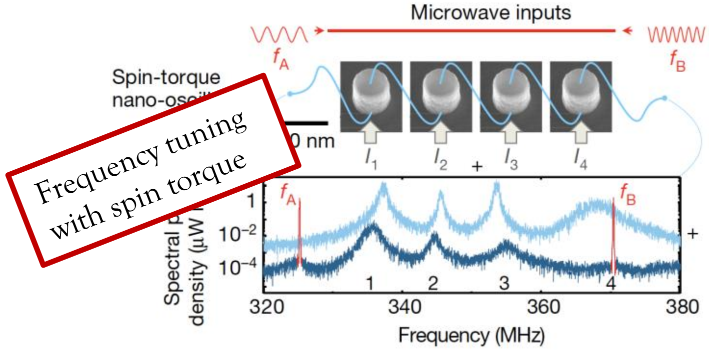
Machine learning



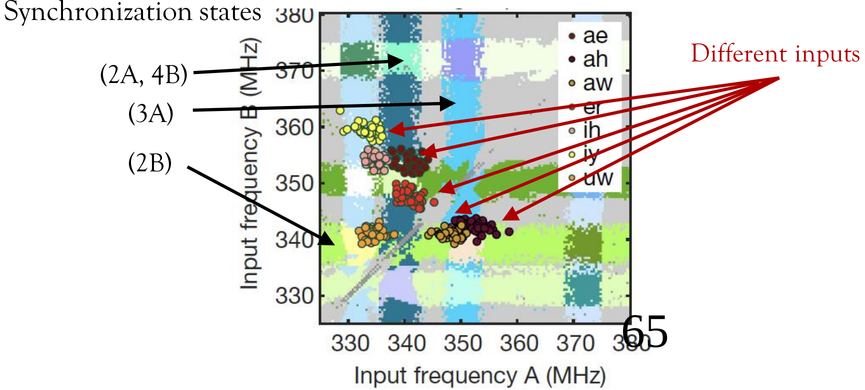


Torrejon et al., Nature 547, 428 (2017)

Coupled nanooscillators for vowel recognition



Synchronization map



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