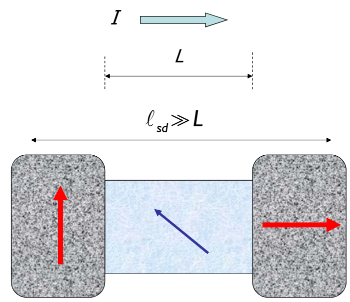
Spin torques and spin pumping

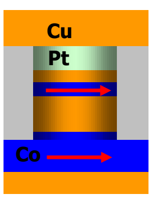
Gerrit Bauer, ESM Part I.2

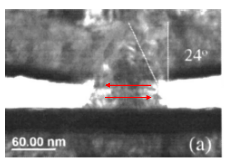
F|N|F spin valves: non-collinear



Current-induced magnetization reversal

Electrical currents can controllably reverse the magnetization in small (< 200 nm) magnetic devices (Slonczewski, Berger):





Current-induced magnetization reversal

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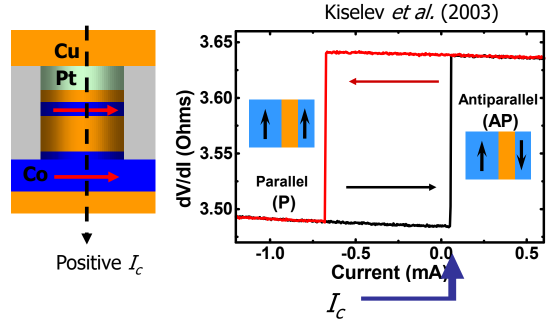
Kiselev *et al.* (2003)



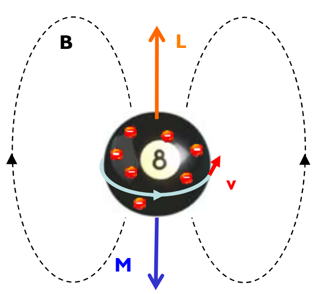
2013 Oliver E. Buckley Condensed Matter Physics Prize

Luc Berger
Carnegie Mellon University

John Slonczewski
IBM Research Staff Emeritus

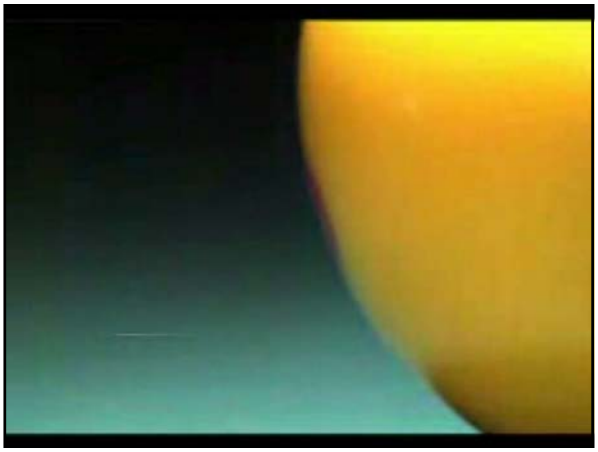
Citation:
"*For predicting spin-transfer torque and opening the field of current-induced control over magnetic nanostructures.*"

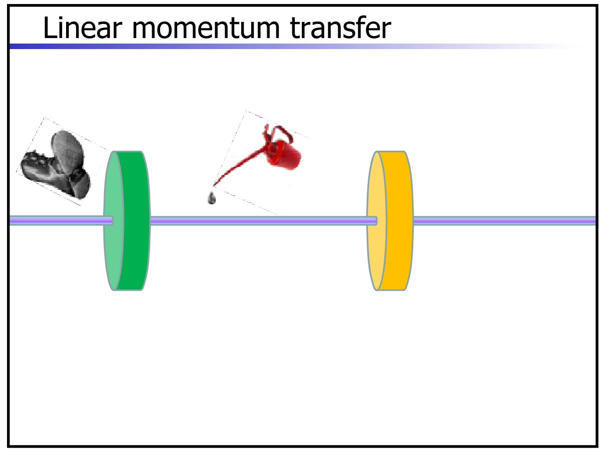
Charged spinning billiard ball

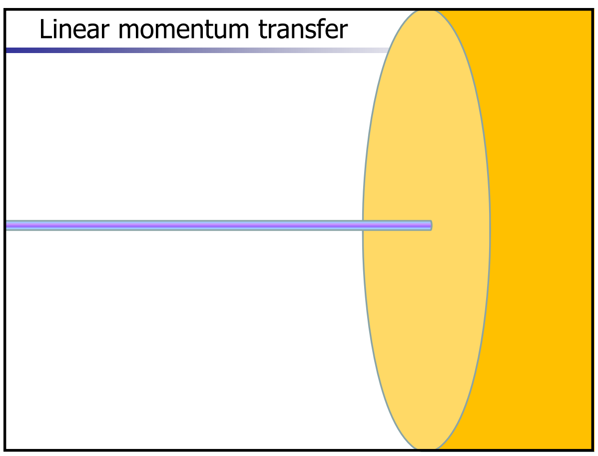


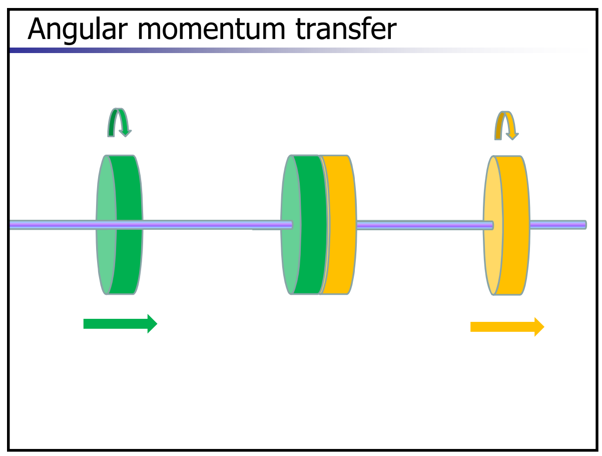
$$\mathbf{M} = \frac{-|e|}{2}\int \frac{d\mathbf{r}}{V}(\mathbf{r}\times\mathbf{v}) = \frac{-|e|}{2m}\mathbf{L}$$

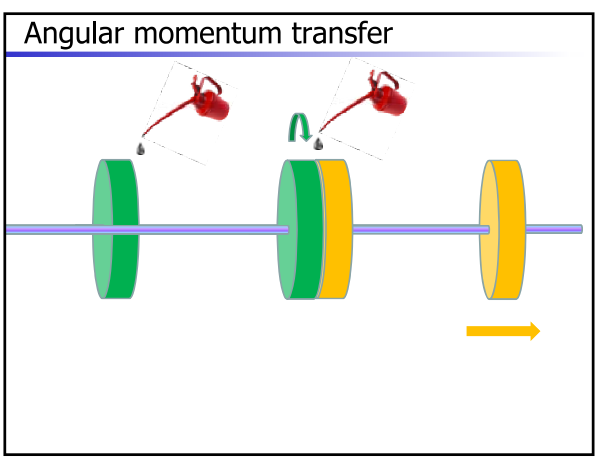
$\gamma = \frac{|e|}{2m}$ gyromagnetic ratio

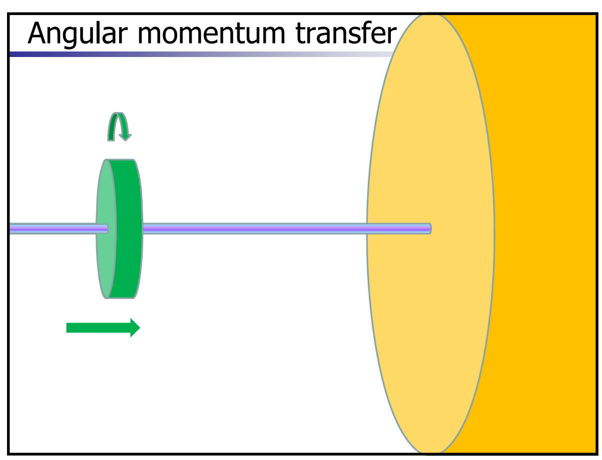


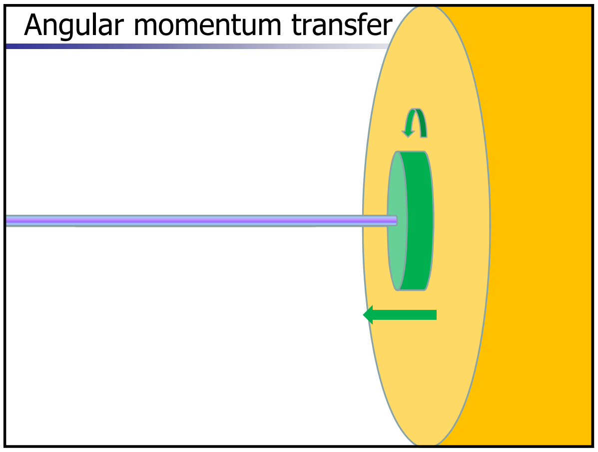

Linear momentum transfer

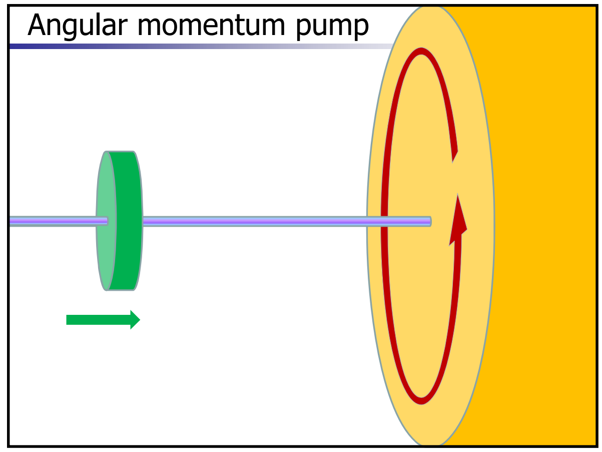

Linear momentum transfer

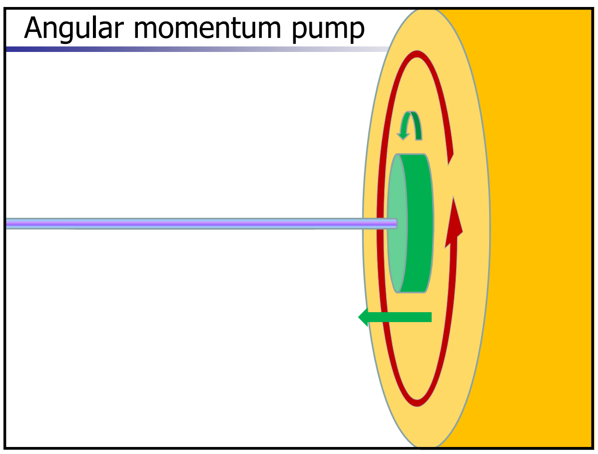

Angular momentum transfer

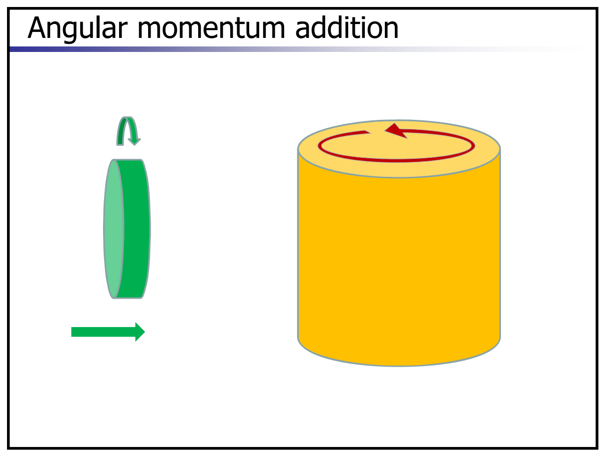

Angular momentum transfer

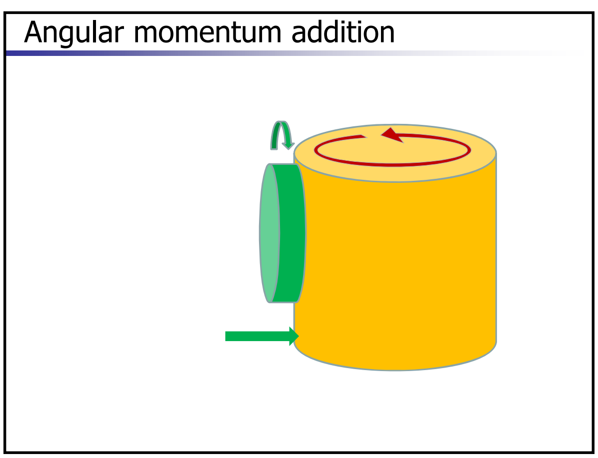

Angular momentum transfer

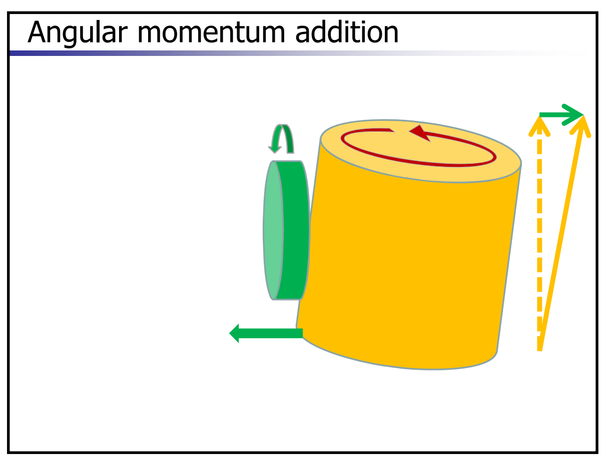

Angular momentum transfer


Angular momentum pump

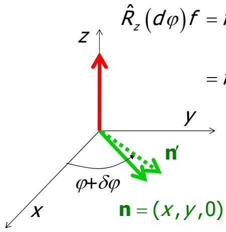

Angular momentum pump


Angular momentum addition


Angular momentum addition


Angular momentum addition

Rotation in quantum mechanics



$$\hat{R}_z(d\varphi)f = f(x+dx, y+dy) = f + \frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy$$

$$= f + \left(-y\frac{\partial}{\partial x} + x\frac{\partial}{\partial y}\right) f d\varphi = \left(1 + \frac{i}{\hbar}\hat{L}_z d\varphi\right) f$$

Finite rotation: $\varphi = \lim_{n\to\infty} n d\varphi$

$$\hat{R}_z(\varphi) = \lim_{n\to\infty}\left(1 + \frac{i}{\hbar}d\varphi\hat{L}_z\right)^n$$

$x' = x + dx = x - y d\varphi$

$y' = y + dy = y + x d\varphi$

$\log(1+x) \approx x$

$\rightarrow \lim_{n\to\infty} \log(1+x)^n \approx \lim_{n\to\infty} nx$

$$\log \hat{R}_z(\varphi) = \lim_{n\to\infty}\frac{i}{\hbar}(n d\varphi)\hat{L}_z = \frac{i}{\hbar}\varphi\hat{L}_z \rightarrow \hat{R}_z(\varphi) = e^{\frac{i}{\hbar}\varphi\hat{L}_z}$$

Rotation in quantum mechanics

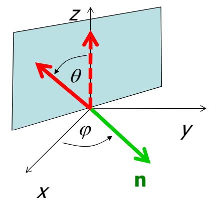
Rotation of a state $|\Psi\rangle$ by an angle θ around an axis with unit vector **n**:

$$|\Psi\rangle_R = \hat{R}_{\mathbf{n}}(\theta)|\Psi\rangle$$

Rotation operator: $\hat{R}_{\mathbf{n}}(\theta) = \exp\left(i\theta\mathbf{n}\cdot\hat{\mathbf{L}}/\hbar\right)$

Electron spin: $\hat{\mathbf{L}} = \mathbf{s} = \frac{\hbar}{2}\boldsymbol{\sigma}$

$$\hat{R}_{\mathbf{n}}(\theta) = e^{i\mathbf{n}\cdot\boldsymbol{\sigma}\theta/2}$$



With $\mathbf{n} = (\cos\varphi, \sin\varphi, 0)$

$$\psi(\varphi,\theta) = \mathbf{R}(\varphi,\theta)\begin{pmatrix}1\\0\end{pmatrix}$$

generates all possible spin states.
Example:

$$|\rightarrow\rangle_x = \mathbf{R}\left(\frac{\pi}{2},\frac{\pi}{2}\right)\begin{pmatrix}1\\0\end{pmatrix}$$

Spins on the Bloch sphere

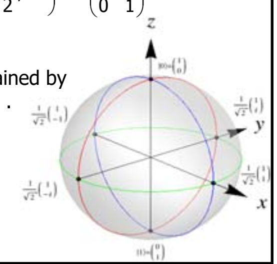
$$\mathbf{R}\left(\frac{\pi}{2},\theta\right) = e^{i\sigma_y\theta/2} = e^{\begin{pmatrix}0&1\\-1&0\end{pmatrix}\theta/2} = \sum_{m=0}^{\infty}\frac{1}{m!}\begin{pmatrix}0&1\\-1&0\end{pmatrix}^m\left(\frac{\theta}{2}\right)^m$$

$$= \begin{pmatrix}\cos\frac{\theta}{2} & -\sin\frac{\theta}{2}\\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2}\end{pmatrix}$$

$$\mathbf{R}\left(\frac{\pi}{2},2\pi\right) = -\begin{pmatrix}1&0\\0&1\end{pmatrix}$$

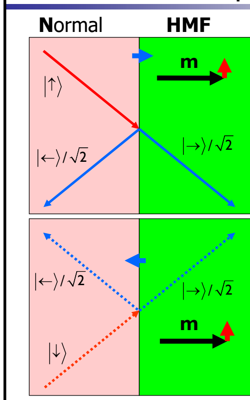
Spin-up state in *x*-direction is obtained by rotation about *y*-axis with $\theta = \pi/2$.

$$|\rightarrow\rangle_x = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$$



Check: ${}_x\langle\rightarrow|\mathbf{s}|\rightarrow\rangle_x = \frac{\hbar}{2}(1,0,0)$

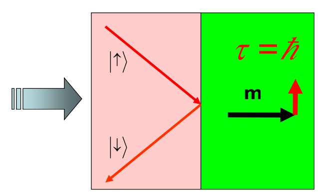
Slonczewski torque in half metals



$|\uparrow\rangle \Rightarrow (|\rightarrow\rangle + |\leftarrow\rangle)/\sqrt{2}$

longitudinal spin current

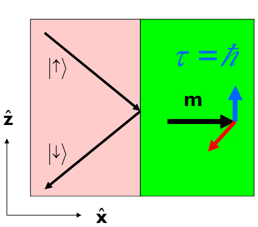
transverse spin current = torque



$$\left|\tau\left(\theta = \frac{\pi}{2}\right)\right| = \frac{Ne}{2\pi}(V_\uparrow - V_\downarrow)$$

N = number of incoming channels

Spin-mixing conductance



$$\tau(\mathbf{m} = \hat{x}) = \hat{z}\frac{\hbar}{e}\frac{e^2N}{h}(V_\uparrow - V_\downarrow)$$

$$G_{\text{Sharvin}} = \frac{2e^2}{h}\sum_{\nu\mathbf{k}^{\rightarrow}}^{E_F} 1 = \frac{2e^2}{h}N$$

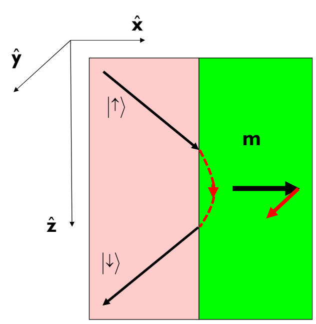
$\mathbf{k}^{\rightarrow}$ incoming wave vectors

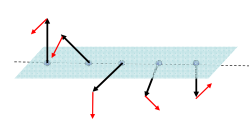
Scattering theory: $\tau(\mathbf{m} = \hat{\mathbf{x}}) = \frac{\hbar}{e}(V_\uparrow - V_\downarrow)\{\hat{\mathbf{z}}\,\mathrm{Re}\,G_{\uparrow\downarrow} + \hat{\mathbf{y}}\,\mathrm{Im}\,G_{\uparrow\downarrow}\}$

Spin mixing conductance: $G_{\uparrow\downarrow} = \frac{e^2}{h}\sum_{\nu\mathbf{k}^{\rightarrow}}^{E_F}\left(1 - r_{\nu\mathbf{k}}^{\uparrow}\left(r_{\nu\mathbf{k}}^{\downarrow}\right)^*\right) \approx \frac{e^2N}{h}$

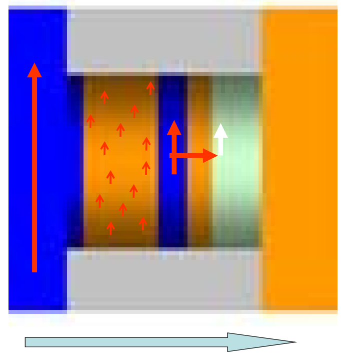
Exchange-field torque

Precession by spins in evanescent states

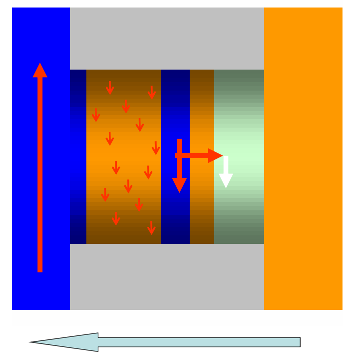




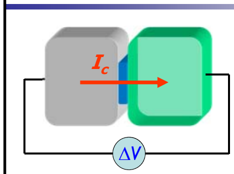
Switching by spin transfer

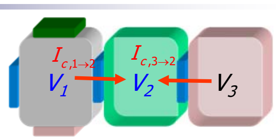


Switching by spin transfer



Ohm's and Kirchhoff's Laws





charge conservation

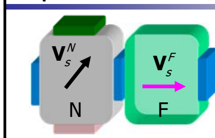
$$\sum_j I_{c,j\to i} = 0$$

Charge current:

$I_{c,1\to2} = G_{1\to2}(V_1 - V_2)$ $G_{1\to2}$ conductance

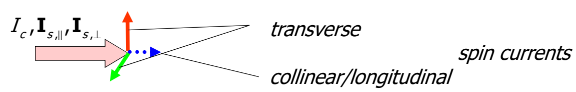
$G = \frac{e^2}{h} g = \frac{e^2}{h}\sum_{nm}|t_{nm}|^2$ Landauer formula

Spin currents



$\mathbf{V}_s^N$ spin accumulation in N

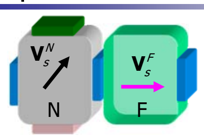
$\mathbf{V}_s^F$ spin accumulation in F ∥ **m** magnetization direction



$$\mathbf{I}_{s,\perp} = 2\operatorname{Re} G_{\uparrow\downarrow}\left(\mathbf{m}\times\mathbf{V}_s^N\times\mathbf{m}\right) + 2\operatorname{Im} G_{\uparrow\downarrow}\left(\mathbf{V}_s^N\times\mathbf{m}\right)$$

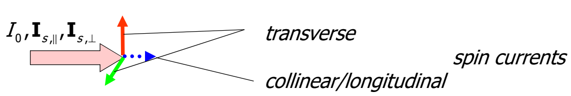
$\tau = -\frac{\hbar}{2e}\mathbf{I}_{s,\perp}$ in-plane (damping)   out-of-plane (effective field)

Spin currents



$\mathbf{V}_s^N$ spin accumulation in N

$\mathbf{V}_s^F$ spin accumulation in F ∥ **m** magnetization direction



$g_s = \sum_{nm}\left|t_{nm}^s\right|^2 = N - \sum_{nm}\left|r_{nm}^s\right|^2$ $s=\uparrow,\downarrow$ spin-dependent Landauer conductances for charge and collinear spin current

$g_{\uparrow\downarrow} = N - \sum_{nm} r_{nm}^{\uparrow}\left(r_{nm}^{\downarrow}\right)^*$ complex spin-mixing conductance for transverse spin current (torque + exchange field)

Pauli matrix notation

$$\left(\hat 1, \hat{\boldsymbol{\sigma}}\right) = \left\{\begin{pmatrix}1&0\\0&1\end{pmatrix}, \begin{pmatrix}0&1\\1&0\end{pmatrix}, \begin{pmatrix}0&-i\\i&0\end{pmatrix}, \begin{pmatrix}1&0\\0&-1\end{pmatrix}\right\}$$

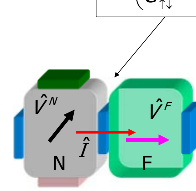
$$\hat X = \begin{pmatrix}X_{\uparrow\uparrow} & X_{\uparrow\downarrow}\\ X_{\uparrow\downarrow}^* & X_{\downarrow\downarrow}\end{pmatrix} = X_c\hat 1 + \mathbf{X}_s\hat{\boldsymbol{\sigma}}$$

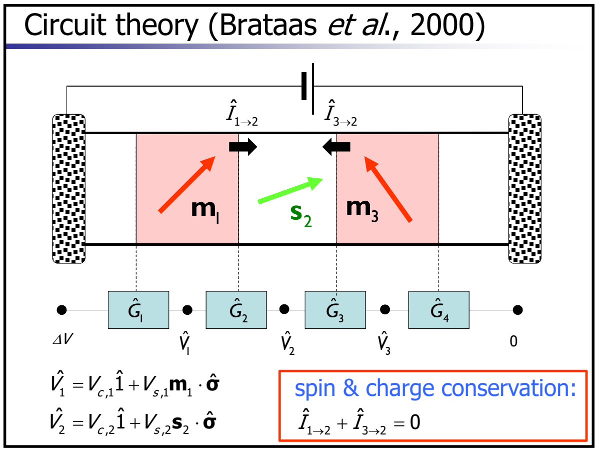
$$\hat V^N = V_c^N\hat 1 + \mathbf{V}_s^N\cdot\hat{\boldsymbol{\sigma}}$$

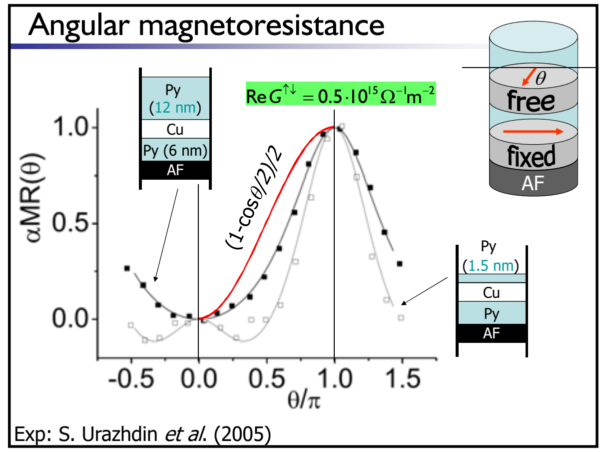
$$\hat V^F = V_c^F\hat 1 + V_s^F\mathbf{m}\cdot\hat{\boldsymbol{\sigma}}$$

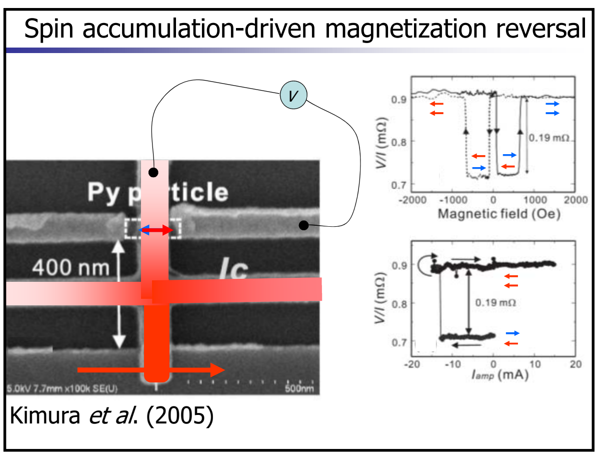
$$\hat I = I_c\hat 1 + \mathbf{I}_s\cdot\hat{\boldsymbol{\sigma}}$$

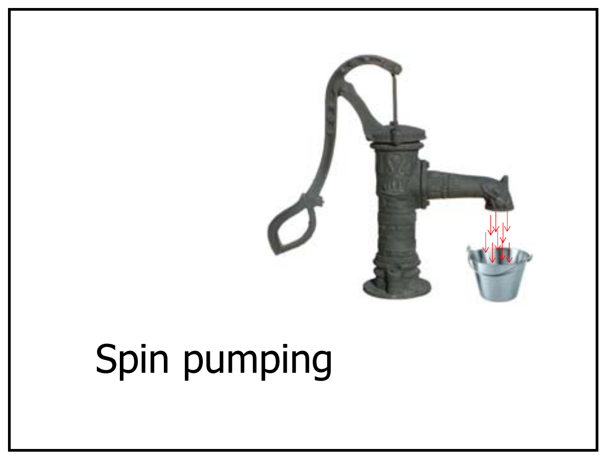
$$\hat G = \begin{pmatrix}G_\uparrow & G_{\uparrow\downarrow}\\ G_{\uparrow\downarrow}^* & G_\downarrow\end{pmatrix}$$

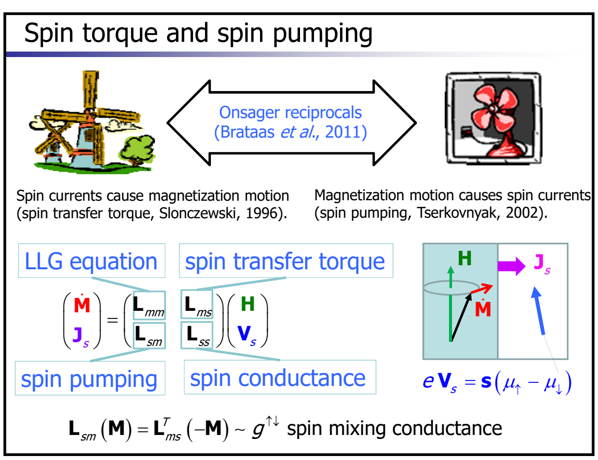


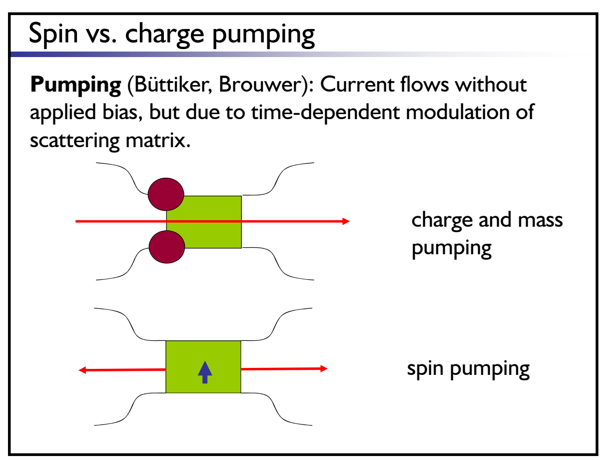

Circuit theory (Brataas et al., 2000)
$\hat{I}_{1\to 2}$
$\hat{I}_{3\to 2}$
$\mathbf{m}_1$
$\mathbf{s}_2$
$\mathbf{m}_3$
$\hat{G}_1$ $\hat{G}_2$ $\hat{G}_3$ $\hat{G}_4$
ΔV $\hat{V}_1$ $\hat{V}_2$ $\hat{V}_3$ 0
$\hat{V}_1 = V_{c,1}\hat{1} + V_{s,1}\mathbf{m}_1 \cdot \hat{\boldsymbol{\sigma}}$
$\hat{V}_2 = V_{c,2}\hat{1} + V_{s,2}\mathbf{s}_2 \cdot \hat{\boldsymbol{\sigma}}$
spin & charge conservation:
$\hat{I}_{1\to 2} + \hat{I}_{3\to 2} = 0$


Angular magnetoresistance
θ
free
fixed
AF
Py (12 nm)
Cu
Py (6 nm)
AF
$\mathrm{Re}\,G^{\uparrow\downarrow} = 0.5\cdot 10^{15}\,\Omega^{-1}\mathrm{m}^{-2}$
αMR(θ)
1.0
0.5
0.0
(1-cosθ/2)/2
-0.5 0.0 0.5 1.0 1.5
θ/π
Py (1.5 nm)
Cu
Py
AF
Exp: S. Urazhdin et al. (2005)

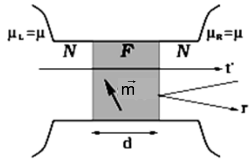

Spin accumulation-driven magnetization reversal
V
Py p ticle
400 nm
Ic
0.9
0.8
0.7
V/I (mΩ)
0.19 mΩ
-2000 -1000 0 1000 2000
Magnetic field (Oe)
-20 -10 0 10 20
I_{amp} (mA)
Kimura et al. (2005)


Spin pumping


Spin torque and spin pumping
Onsager reciprocals
(Brataas et al., 2011)
Spin currents cause magnetization motion
(spin transfer torque, Slonczewski, 1996).
Magnetization motion causes spin currents
(spin pumping, Tserkovnyak, 2002).
LLG equation
spin transfer torque
$\begin{pmatrix}\dot{\mathbf{M}}\\ \mathbf{J}_s\end{pmatrix} = \begin{pmatrix}\mathbf{L}_{mm} & \mathbf{L}_{ms}\\ \mathbf{L}_{sm} & \mathbf{L}_{ss}\end{pmatrix}\begin{pmatrix}\mathbf{H}\\ \mathbf{V}_s\end{pmatrix}$
spin pumping
spin conductance
H
$\mathbf{J}_s$
M
$e\mathbf{V}_s = \mathbf{s}(\mu_\uparrow - \mu_\downarrow)$
$\mathbf{L}_{sm}(\mathbf{M}) = \mathbf{L}_{ms}^T(-\mathbf{M}) \sim g^{\uparrow\downarrow}$ spin mixing conductance

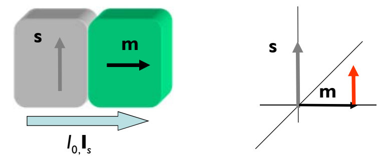

Spin vs. charge pumping
Pumping (Büttiker, Brouwer): Current flows without applied bias, but due to time-dependent modulation of scattering matrix.
charge and mass pumping
spin pumping

Spin pumping



$$\vec{I}_{pump}^{F\to N} = \frac{\hbar}{4\pi} g_{\uparrow\downarrow} \mathbf{m} \times \frac{d\mathbf{m}}{dt}$$

Dynamics of bilayers



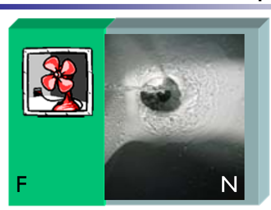
Landau-Lifshitz-Gilbert equation with new torque term:

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m}\times\mathbf{B} + \alpha_0 \mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t} + \frac{\hbar\gamma}{4\pi M}\mathbf{m}\times\left(\mathbf{I}_s^{bias} + \mathbf{I}_s^{pump}\right)\times\mathbf{m}$$

$$= -\gamma \mathbf{m}\times\mathbf{B} + \left(\alpha_0 + \frac{\hbar\gamma}{4\pi M} g_{\uparrow\downarrow}\right)\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t} + \frac{\hbar\gamma}{4\pi M} g_{\uparrow\downarrow}\mathbf{m}\times\mathbf{s}\times\mathbf{m}$$

spin pumping — Slonczewski torque

Sources and sinks of spin currents



$$\frac{\partial \mathbf{m}}{\partial t} = -\mathbf{m}\times\gamma\mathbf{H} + \alpha_0 \mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t} + \tau$$

$$\tau = \tau_{sp} + \tau_{stt}$$

$\tau_{sf} \to \infty$

$\lambda_{sd}/d_N \gg 1$

$$\frac{\partial \mathbf{m}}{\partial t} = -\mathbf{m}\times\gamma\vec{H} + \alpha_0 \mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t}$$

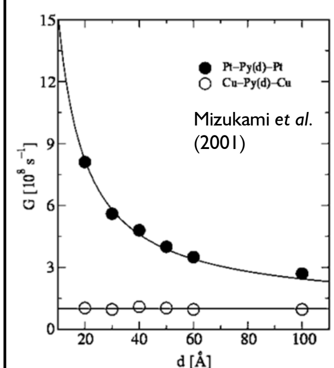
enhanced damping

$\tau_{sf} \to 0$

$\lambda_{sd}/d_N \ll 1$

$$\frac{\partial \mathbf{m}}{\partial t} = -\mathbf{m}\times\gamma\mathbf{H} + \left(\alpha_0 + \frac{\hbar\gamma}{4\pi M_s} g_{\uparrow\downarrow}\right)\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t}$$

Py|Pt mixing conductance



$G = \gamma M_s \alpha$

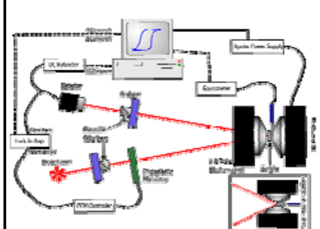
$$G(d) = G_0 + \frac{(g_L \mu_B)^2}{e^2}\frac{G_r^{\uparrow\downarrow}}{Ad}$$

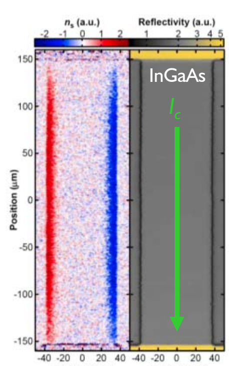
$g_L = 2.1 \quad G_0 = 10^8\,Hz$

Py|Pt:

$$\frac{G_r^{\uparrow\downarrow}}{A} = 1.0\cdot 10^{15}\,\Omega^{-1}m^{-2}$$

Kato *et al.* (2004)



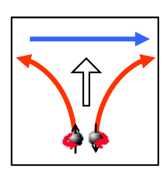


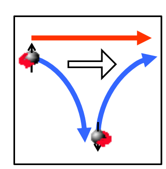
Spin current tensor, spin Hall angle

$$\vec{J}_s = \left(\mathbf{J}_s^x, \mathbf{J}_s^y, \mathbf{J}_s^z\right) = \begin{pmatrix}\mathbf{J}_{s,x}\\ \mathbf{J}_{s,y}\\ \mathbf{J}_{s,z}\end{pmatrix}$$

$\mathbf{J}_s^x$ polarization of current || x

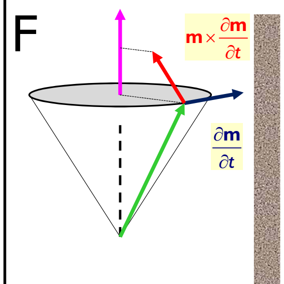
$\mathbf{J}_{s,x}$ current direction of polarization || x

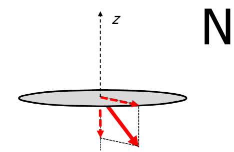




$$\mathbf{J}_{s,\beta} = \theta_{SH}\hat{\boldsymbol{\beta}}\times\mathbf{J}_c \qquad \mathbf{J}_c = \theta_{SH}\sum_\alpha \mathbf{J}_s^\alpha \times\hat{\boldsymbol{\alpha}}$$

Spin pumping





$$\frac{\partial \mathbf{m}}{\partial t} = -\mathbf{m}\times\gamma\mathbf{H} + \alpha_0\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t}$$

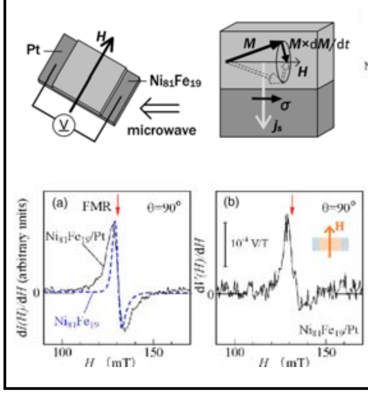
$$\mathbf{I}_{sp} = \frac{\hbar}{4\pi} g_{\uparrow\downarrow}\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t}$$

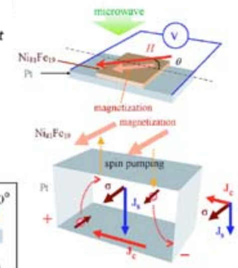
$$\mathbf{I}_{sp}^{DC} = \hat{\mathbf{z}}\frac{\hbar\omega}{4\pi} g_{\uparrow\downarrow} sin^2\theta$$

$$\mathbf{I}_{sp}^{AC} = -\frac{\hbar\omega}{4\pi} g_{\uparrow\downarrow} sin\theta \left[\hat{\mathbf{x}}\sin(\omega t) - \hat{\mathbf{y}}\cos(\omega t)\right]$$

Jiao *et al.* (2013)

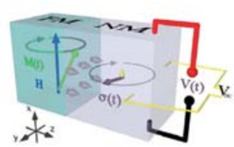
Spin pumping detected by inverse spin Hall effect



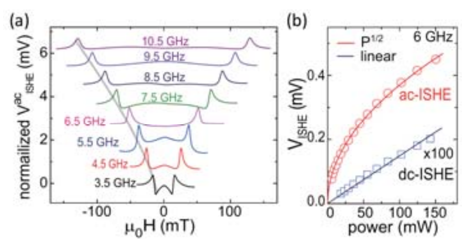


Saitoh et al. (2006)

ac spintronics



Wei *et al.* (2013)
Hahn *et al.* (2013)

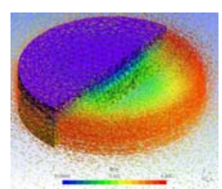


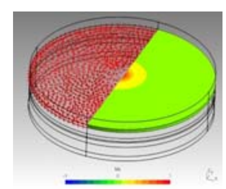
Exchange-only theory is complete

Kyung-Jin Lee
Thierry Valet

SpinFlow3D
in silicio

- Integration of dynamic spin currents with micromagnetics (including Oersted fields)





Spin oscillators

Kyung-Jin Lee *et al.* (2013)