Spin Battery Operated by Ferromagnetic Resonance

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Collaboration:

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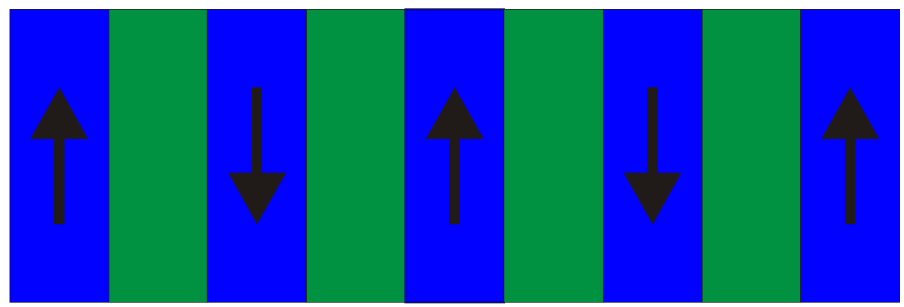
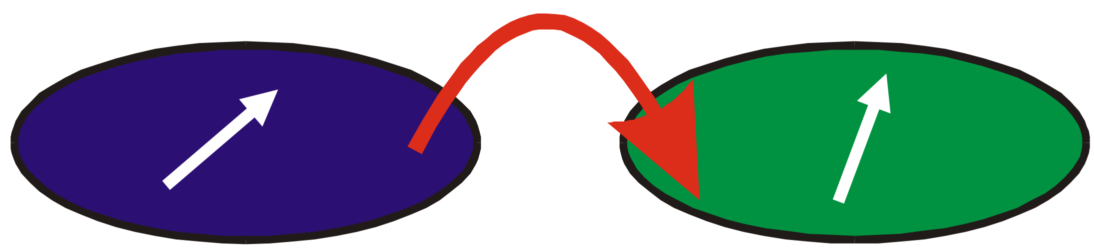
Giant magnetoresistance
(GMR)



Tunnel magnetoresistance
(TMR)

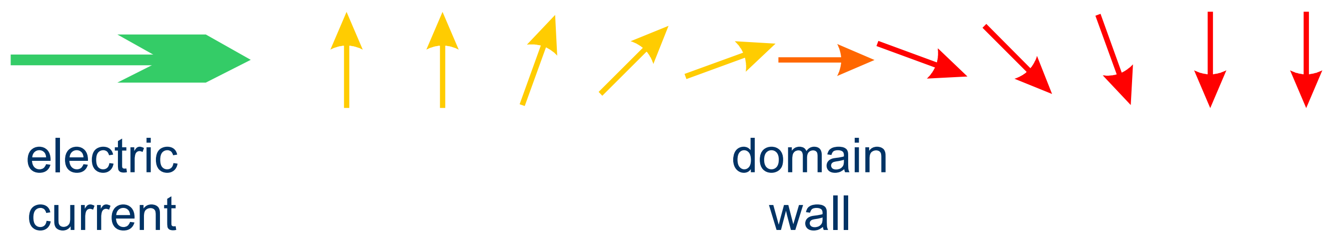


SAN JOSE, Calif., Nov. 10, 1997: IBM today announced the world's highest capacity desktop PC disk drive with new breakthrough technology called "Giant Magnetoresistive (GMR)" heads.

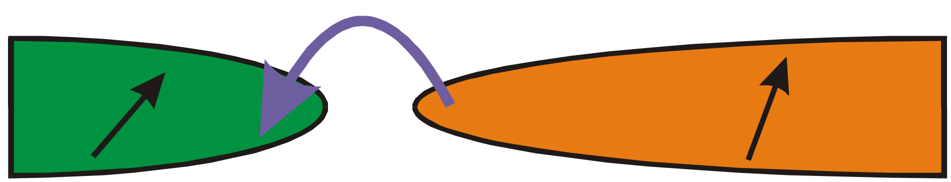
Spin Torque

Cause and effect, Newton's third law:

L. Berger: Domain wall resistance ⟷ Force on the domain wall



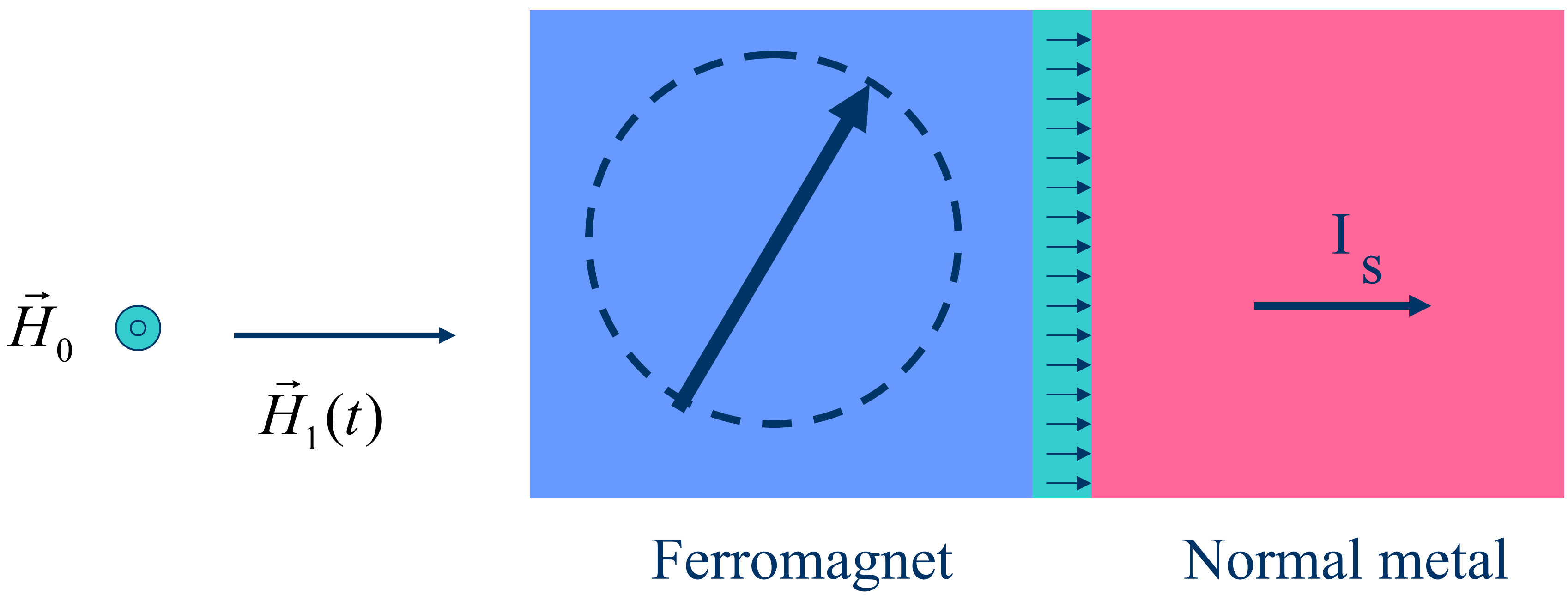
J. Slonczewski: Discrete system, tunnel contact.



Ferromagnetic Resonance

Rotating magnetization direction: $\vec{m}(t)$

Static magnetic field: $\vec{H}_0$ Rotating magnetic field : $\vec{H}_1(t)$



Spin Pumping: Abrupt Change

Population of spin-up and spin-down bands in equilibrium:

Abruptly reverse the magnetization direction:

Scattering Matrix Approach

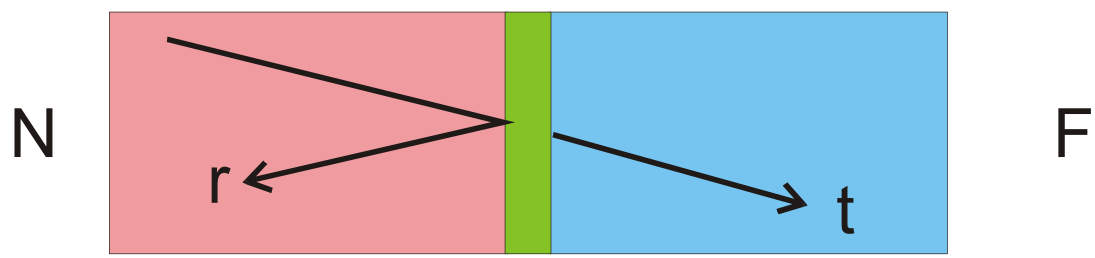
$$\hat{S}_{nm} = \begin{pmatrix} \hat{r}_{nm} & \hat{t}_{nm} \\ \hat{t}_{nm}' & \hat{r}_{nm}' \end{pmatrix}$$

No spin-flip:

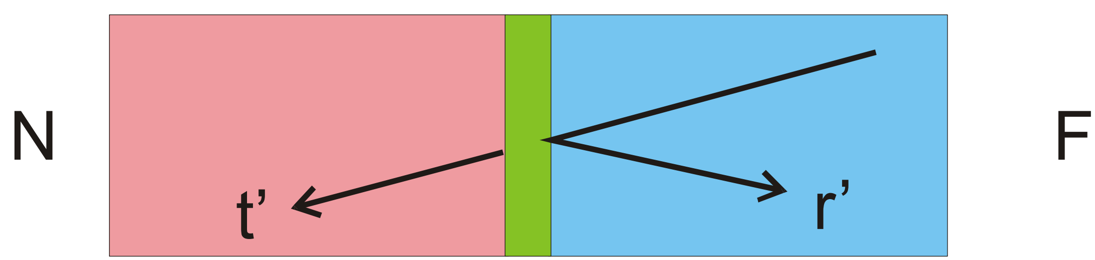
$$\hat{S} = S^{\uparrow}\hat{u}^{\uparrow} + S^{\downarrow}\hat{u}^{\downarrow}$$

$$\hat{u}^{\uparrow} = \left(1 + \vec{\sigma}\cdot\vec{m}\right)/2$$
$$\hat{u}^{\downarrow} = \left(1 - \vec{\sigma}\cdot\vec{m}\right)/2$$

Incoming wave: Normal metal



Incoming wave: Ferromagnet



Adiabatic Spin Pump

2x2 current due to adiabatic change of parameter *X(t)*

$$\hat{I}^{PUMP}(t) = e\frac{\partial \hat{n}}{\partial X}\frac{dX(t)}{dt}$$

The emissitivy is

$$\frac{\partial \hat{n}}{\partial X} = \frac{1}{4\pi i}\sum_{mn,J}\left(\frac{\partial \hat{S}_{mn,NJ}}{\partial X}\hat{S}_{mn,NJ} - \hat{S}_{mn,NJ}\frac{\partial \hat{S}_{mn,NJ}}{\partial X}\right)$$

There is no pumping of charge. The spin-current is

$$\vec{I}_s^{PUMP} = \frac{\hbar}{4\pi}\left(A_r + A_i\vec{m}\times\right)\left(\vec{m}\times\frac{d\vec{m}}{dt}\right)$$

$$A_r = \frac{1}{2}\sum_{nm}\left[\left|r_{nm}^{\uparrow} - r_{nm}^{\downarrow}\right|^2 + \left|t'^{\uparrow}_{nm} - t'^{\downarrow}_{nm}\right|^2\right] \qquad A_i = \mathrm{Im}\sum_{nm}\left[r_{nm}^{\uparrow}\left(r_{nm}^{\downarrow}\right)^* + t'^{\uparrow}_{nm}\left(t'^{\downarrow}_{nm}\right)^*\right]$$

Spin Pumping

Magnetization precession induces spin-current into normal metal

1) No spin-dissipation in the normal metal

Spin accumulation, spin-injection, spin-battery

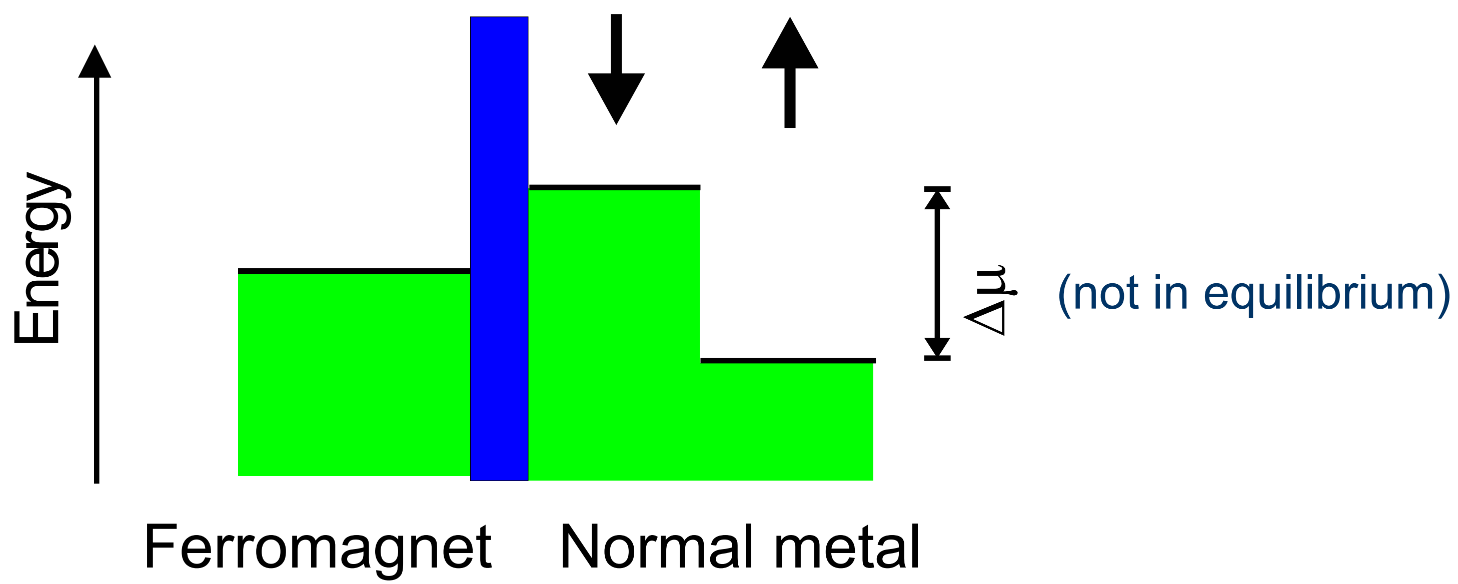
2) Perfect spin-dissipation when the spins relax in the normal metal

Enhanced Gilbert damping in Ferromagnet

Spin Accumulation

$$s = N\Delta\mu$$

N Density of states



Source Current and Back Flow

Diffusion contribution and time-dependent contribution:

$$\vec{I}_s = \vec{I}_s^{\,\text{source}} - \vec{I}_s^{\,\text{back}}$$

Constant magnetization:

$$\vec{I} = -\vec{I}_s^{\,\text{back}}, \quad \vec{I}^{\,\text{source}} = 0$$

Diffusion process

No non-equilibrium occupation:

$$\vec{I}_s = \vec{I}_s^{\,\text{source}}, \quad \vec{I}_s^{\,\text{back}} = 0$$

Adiabatic spin pumping

Boundary Condition for Spin Flow

Transport regime:
Ferromagnet larger than the ferromagnetic coherence length.
Ferromagnet smaller than longitudinal spin-flip relaxation length.

Spin pumping:

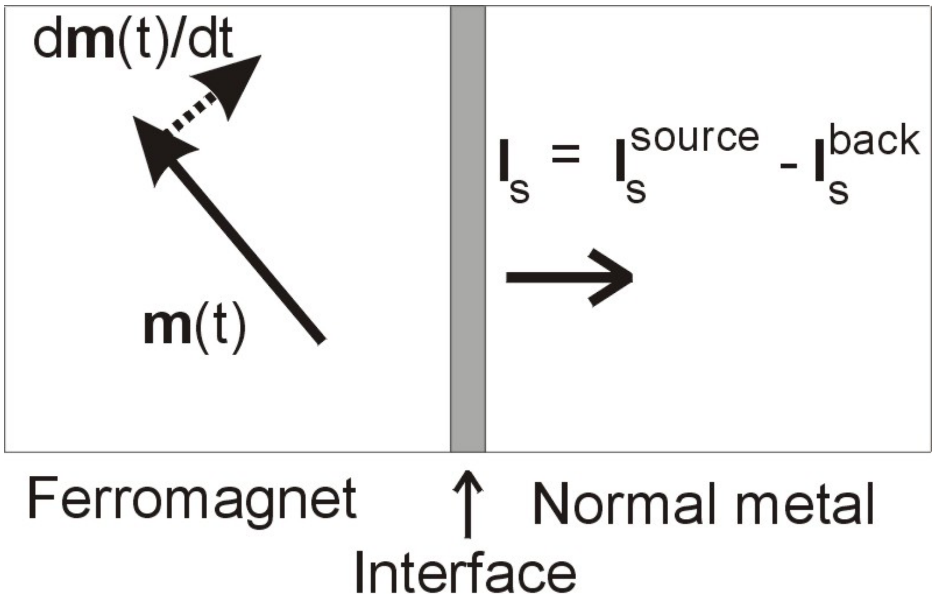
$$\vec{I}_s^{\,\text{source}} = \frac{\hbar}{4\pi} g_{\uparrow\downarrow} \vec{m} \times \frac{d\vec{m}}{dt}$$

Backflow [PRL **84**, 2481 (2000)]:

$$\vec{I}_s^{\,\text{back}} = \frac{g_{\uparrow\downarrow}}{2\pi N}\left[\vec{s} - \vec{m}\left(\vec{m}\bullet\vec{s}\right)\right]$$

Mixing conductance

$$g_{\uparrow\downarrow} = \sum_{nm}\left[\delta_{nm} - r_{nm}^{\uparrow}\left(r_{nm}^{\downarrow}\right)^{*}\right]$$



Spin Diffusion in Normal Metal

$$\frac{\partial \vec{s}}{\partial t} = D\frac{\partial^2 \vec{s}}{\partial x^2} - \frac{\vec{s}}{\tau_s}$$

Boundary condition at F-N interface: $$\left(DA\hbar\frac{\partial \vec{s}}{\partial x}\right)_{x=0} = \vec{I}_s = \vec{I}_s^{\,\text{source}} - \vec{I}_s^{\,\text{back}}$$

Boundary condition at the end of the sample: $$\left(DA\hbar\frac{\partial \vec{s}}{\partial x}\right)_{x=0} = 0$$

Spin bias: $$\Delta\vec{\mu} = \frac{2\vec{s}}{N}$$

The spin-current and the accompanying spin-bias have AC and DC components.

Spin Battery

The frequency harmonics of the spin bias are strongly suppressed when

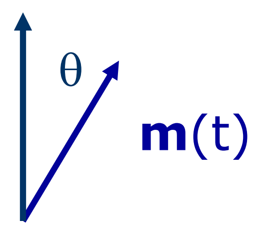
$$l_{\mathrm{s}}\left(\omega\tau_{\mathrm{s}}\right)^{-1/2} < L < l_s$$

which is satisfied when

$$\tau_s > \omega \sim 10^{-11} s / H_0(T)$$

The spin-bias is then:

$$\left\langle \Delta\vec{\mu} \right\rangle_t = \hbar\omega \frac{\sin^2\theta}{\sin^2\theta + \gamma}$$



θ: FMR precession cone angle

ω: cyclotron frequency

Spin Bias

Reduction factor: $$\gamma = \frac{\tau_i}{\tau_s} \frac{\tanh(L/l_s)}{L/l_s}$$

Spin-injection rate: $$\tau_i^{-1} = \frac{g_{\uparrow\downarrow}}{2\pi\hbar NAL}$$

Large systems have a smaller injection rate since more states have to be filled.

Metallic contact: The mixing conductance is

$$g_{\uparrow\downarrow} = \kappa \frac{Ak_F^2}{4\pi}, \quad \kappa \sim 1$$

$$\frac{\tau_\mathrm{i}}{\tau_\mathrm{s}} = \sqrt{\frac{8}{3}} \frac{1}{\kappa} \sqrt{\varepsilon} \frac{L}{l_\mathrm{s}}, \quad \varepsilon = \frac{\tau}{\tau_\mathrm{s}}$$

Spin Bias

$$\langle \Delta\vec{\mu} \rangle_t = \hbar\omega \frac{\sin^2\theta}{\sin^2\theta + \gamma}$$

The maximum spin bias is realized when $L \gg l_s$ ($\gamma \to 0$):

$$\langle \Delta\vec{\mu} \rangle_t = \hbar\omega$$

Typical resonance frequencies (H_0=1.0T): $\hbar\omega \approx 0.1$ meV

Example: L/l_s= 10 gives θ>6 degrees.

Al: $l_s \sim 1\mu$m

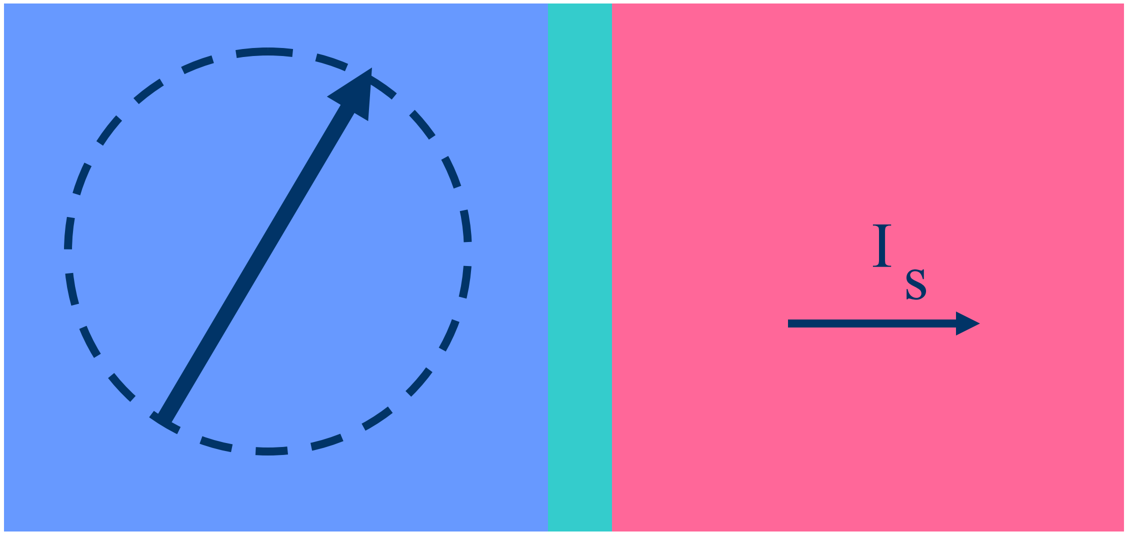
Cu: $l_s \sim 1\mu$m

GaAs: $\tau_s \sim 10^{-7}\,s$ at $n = 5\times10^{16}\,\mathrm{cm}^3$

Si: $l_s \sim$ very long

Ferromagnetic Resonance

$$\left(\frac{\partial \vec{m}}{\partial t}\right) = -\vec{m} \times H_{\text{eff}} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t}$$



α is *enhanced* in thin films

$$\alpha = \alpha_0 + \alpha'$$

$$\alpha' = \frac{g_L A_r}{4\pi M},$$

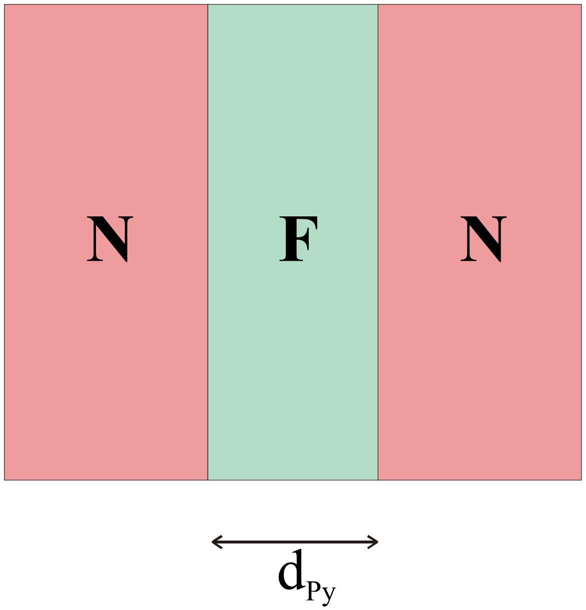
$$A_r = \frac{1}{2} \sum_{nm} \left[\left| r_{nm}^{\uparrow} - r_{nm}^{\downarrow} \right|^2 + \left| t'^{\uparrow}_{nm} - t'^{\downarrow}_{nm} \right| \right]$$

Comparison with Experiments

Exp: S. Mizukami, Y. Ando,
T. Miyazaki

Measure Ferromagnetic Resonance Linewidth vs. width of ferromagnet

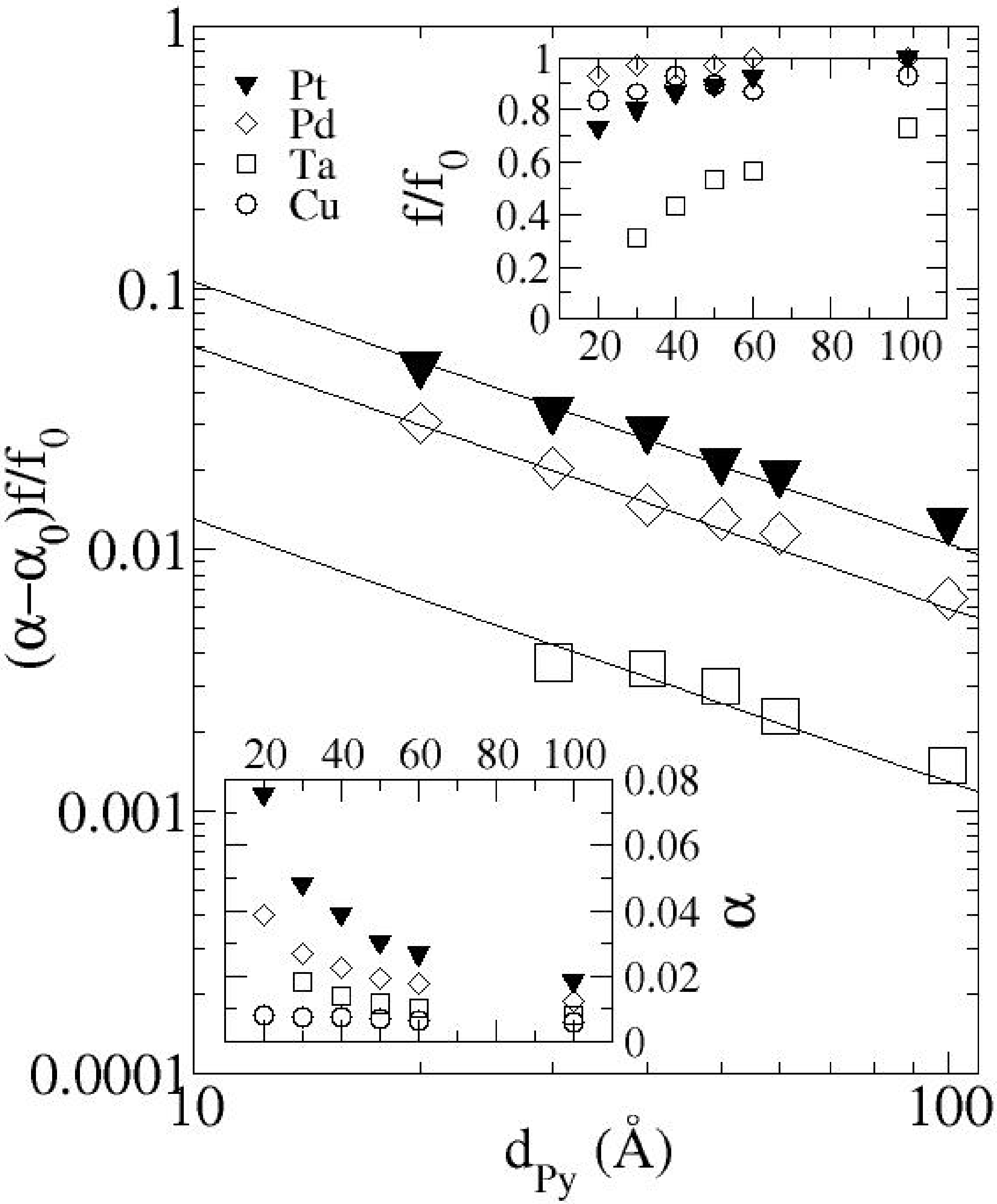
Also see experiments by Bret Heinrich et al.



Our estimate :

$$\mathrm{Py}: \quad f = 1.2, \quad g_L = 2.1$$

$$\alpha' = 0.3 / d_{\mathrm{Py}}(A)$$



Pt
Pd
Ta
Cu
$(\alpha-\alpha_0)f/f_0$
d_{Py} (Å)
10
100
1
0.1
0.01
0.001
0.0001
f/f_0
0
0.2
0.4
0.6
0.8
1
20
40
60
80
100
α
0
0.02
0.04
0.06
0.08

Conclusions

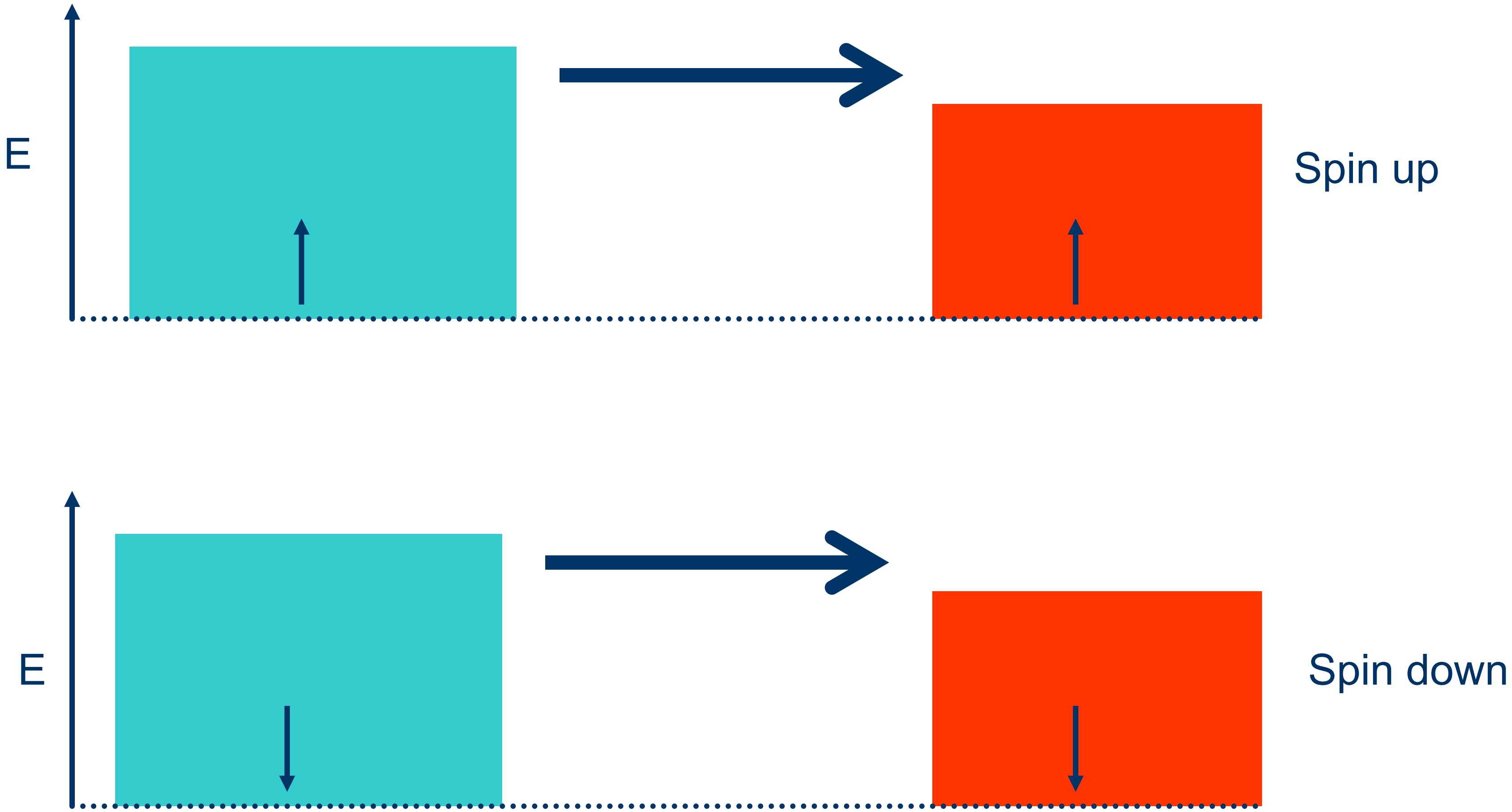
A precessing magnetization emits spin-currents from the ferromagnet into adjacent conductors.

Spin-accumulation when the spin-injection rate is faster than the spin-flip relaxation rate, which is feasible in metals and semiconductors.

Enhanced Gilbert damping when the normal metal is a spin sink.

- Phys. Rev. Lett. **88**, 117601 (2002).
- Phys. Rev. B **65**, 22401(RC) (2002).
- Phys. Rev. B **66**, 060404 (RC) (2002).
- Phys. Rev. Lett **84**, 2481 (2000).

Charge Battery



Spin Battery